SHORT- AND LONG-TERM EFFECTS OF ALTERNATIVE SILVICULTURAL SYSTEMS ON STAND DEVELOPMENT OF LOWLAND BLACK SPRUCE FORESTS IN NORTHERN MINNESOTA, USA

A THESIS SUBMITTED TO THE FACULTY OF
THE UNIVERSITY OF MINNESOTA BY

Brian David Anderson

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF MASTER OF SCIENCE OF
NATURAL RESOURCE SCIENCE AND MANAGEMENT

Dr. Matthew Russell
Dr. Marcella Windmuller-Campione

May, 2018

Acknowledgements

Many individuals deserve my gratitude for their tremendous support and impacts they had on me during this project. I am greatly thankful to my advisors, Matthew Russell and Marcella Windmuller-Campione, for the wonderful balance of support and freedom to take this project and my course of study in the direction of my interests. Additionally, thank you for the support not just in this project work, but also through the support and means to attend meetings and conferences outside of the University that provided me with a well-rounded education. Thank you to my committee members Robert Blanchette and Brian Palik for their expertise and feedback, and being willing to work across disciplines.

Douglas Kastendick with the United States Forest Service (USFS) Northern Research Station provided copious amounts of field reconnaissance help, organization, and help in locating project records. Stephanie Patton, Research Fellow with the University of Minnesota, was gracious enough to accompany me in black spruce bogs on every day of fieldwork. I quite literally could not have completed the fieldwork without your help. Thank you to tremendous fieldwork staff from multiple agencies: Tom Heffernen, Katy Johnson, and Julian Teagarden with the USFS, Alexis Peasley and Zach Suelter with the Minnesota Department of Natural Resources (MnDNR), and Irene de Pellegrin Llorente and Sara Kelso of the University of Minnesota. It was a pleasure to work across agency lines on an experimental forest that has truly been collaborative since its beginnings. Thank you to Jaden Hoeft and Anastasia Shimkus, University of Minnesota students, for data entry.

I wish also to thank several groups of individuals for their support and collaboration. First, thank you to the University of Minnesota Silviculture, Forest Health, & Biometrics Lab Group for valuable collaboration through sharing of your work and feedback on my work, and for comradery throughout my time in the program. Thank you to the wonderful faculty and staff in the Department of Forest Resources and Natural Resource Science and Management graduate program for fostering a supportive community of collaboration. Also, thank you to the Department of Forest Resources for the Fellowship. Finally, thank you to a special group of officemates in Stephanie Patton, Irene de Pellegrin Llorente, Ryan Toot, Justin Meier, and Benjamin Pflughoeft for a true community of fellow learners. Your consistent feedback—both formal and informal—questions, ideas, thoughts, and queries have advanced my learning as much as any official class could.

Thank you to the US Forest Service and the MnDNR for their collaboration in and support of this work. It is a personal pleasure of mine to work across institutional lines and accomplish more through collaboration than we can separately.

Lastly, thank you to my wife Christi for your consistent support in all that I do and your irreplaceable companionship. Your encouragement has literally been life changing and has helped me improve in many areas as a person.

Table of Contents

List of Tables

List of Figures

Chapter 1 Introduction

Black spruce (*Picea mariana* (Miller) B.S.P.) is an important species economically and ecologically in Minnesota (Viereck and Johnston 1990). The black spruce cover type occurs over vast portions of northern Minnesota's landscape, as well as portions of the adjacent Lake States and large portions of the boreal forest in Canada. Black spruce is a slow-growing species with a longer average lifespan than a typical forester's career. Therefore, long-term studies in black spruce are rare across its range. Furthermore, studies seeking to understand that various many forms of forest management in black spruce are few and far between, particularly in the Lake States (Minnesota, Michigan, Wisconsin).

Studies in Canada to understand the effects of alternative silvicultural systems and their possible role in black spruce stands have been increasing over the last few decades (e.g., Groot 1995, 2014; MacDonell and Groot 1997; Cimon-Morin et al. 2010; Soucy et al. 2012; Lafleur et al. 2016). This represents a significant step forward in studies in black spruce; however, these studies have been largely in Canada where soil, climate, and other physiographic conditions are different than in the Lake States; the impact that these differences may have on black spruce stand dynamics are unknown (Viereck and Johnston 1990).

Likewise there are few studies in black spruce growth and yield in the Lake States (Perala 1971). Models to predict tree growth and future sizes of trees help managers make important decisions in terms of management type and length of harvest rotations. Recent work to model diameter growth of black spruce was undertaken as part of a larger effort to improve model performance in Lake States species (Deo and Froese 2013).

This study aims to take advantage of a study established in the mid-20th century in northern Minnesota investigating a number of alternative silvicultural systems in lowland black spruce. “The Compartment Study” has not been studied or managed since the last 1960s, but black spruce grows slowly and 60 years after the last treatments provides an excellent opportunity to see long-term stand dynamics. Additionally, a ten-year re-measurement period in the original study provides perfect data to fit a diameter growth model to lowland black spruce. Chapter 2 examines ten-year diameter growth differences between treatments and aims to adapt and fit a ten-year diameter growth model for lowland black spruce in northern Minnesota. The purpose of Chapter 3 is to quantify the short- and long-term effects of alternative silvicultural treatments on the composition and structure of lowland black spruce stands. Chapter 4 summarizes the results of the investigation and provides implications for management of the black spruce resource in northern Minnesota and the Lake States.

Chapter 2 Assessing ten-year diameter growth and fitting mixed-effects non-linear models to predict ten-year diameter growth

Introduction

Black spruce (*Picea mariana*) is distributed broadly across North American boreal forests and is an important species both economically and ecologically (Viereck and Johnston 1990). Black spruce is the most important pulpwood species in Canada, and is an important commercial species in the Lake States region (Michigan, Minnesota, and Wisconsin) of the United States (Viereck and Johnston 1990). In Minnesota, black spruce comprises 648,000 hectares (1.6 million acres) of the 7.04 million forested hectares (17.4 million acres) (Miles 2017) and is the second-most harvested pulpwood species by volume (Minnesota Department of Natural Resources 2017).

Considering its large presence in northern Minnesota, understanding the productivity of black spruce stands under a variety of conditions is important. The size and growth of black spruce trees varies widely depending on latitude, soils, and climate. On high quality sites, lowland black spruce in Minnesota can reach a diameter at breast height (1.3 m above the ground; dbh) of 35 cm, and a total height of 24 meters. However, mature stands typically contain trees with diameters of 13 to 23 cm, and heights of 15 to 20 meters (Heinselman 1957). Stand yields vary greatly depending on site index, basal area, and age. In a 120-year old stand with a density of 41 m^2 ha^{-1} basal area, yields range from 413 m^3 ha^{-1} in a stand with site index of 14 meters at 50 years, to 217 m^3 ha^{-1} in the same stand at a site index of 7.5 meters (Perala 1971).

Individual tree diameter increment can be affected by numerous tree and stand level variables as well as differing silvicultural systems that managers may use. In Canada, there has been increased interest to understand these impacts in upland and lowland black spruce forests. For example black spruce diameter growth is influenced by spatial position in a stand, position relative to skidding trails, competition, growth prior to cutting, diameter, and tree age (Vincent et al. 2009; Pamerleau-Couture et al. 2015; Girona et al. 2016). In response to silvicultural systems, Groot and Hokka (2000) demonstrated that average diameter growth of advance regeneration in uneven-aged black spruce stands in Canada responds positively over a ten-year period following overstory removal, peaking at ten years and slowly declining to near pre-harvest levels. Black spruce individual diameter growth responds favorably to a variety of treatments, including thinning, shelterwoods, and partial selection cuts (Thorpe and Thomas 2007; Vincent et al. 2009; Girona et al. 2016).

Due to its wide geographical range, conditions in which black spruce stands grow in the Lake States differs greatly from those reported in the recent black spruce research published from Canada. Lake States black spruce almost exclusively grows in peat bogs and swamps, and are growing at the southern and western edge of its range resulting in different precipitation and temperature extremes and norms. Despite its abundance and importance in the Lake States, studies in black spruce silviculture and growth and yield in the region are few over the last 40 years. A sizable amount of work was done in the mid-20th century studying both the use of alternative silvicultural systems and growth and yield (Schantz-Hansen 1931; Fox and Kruse 1933; LeBarron 1945; Perala 1971). Yield tables published by the US Forest Service in 1971 are also commonly used today (Perala 1971).

Predicting diameter growth is important for land managers to understand future productivity in a variety of conditions. Individual tree diameter growth models are used in many forest modeling systems, notably the US Forest Service Forest Vegetation Simulator (FVS) program (USDA Forest Service 2013). Work by Deo and Froese (2013) to improve model fitting for trees over 12.7 cm (5 in) dbh for Lake States species, including black spruce, is being transitioned into use in FVS (Dixon and Keyser 2017). Despite this work, little is known about the effects of silvicultural treatments on individual tree diameter growth.

The objective of this study is to quantify the effects of six silvicultural treatments and a variety of tree and stand-level variables on individual black spruce diameter growth, and to assess the performance of non-linear mixed effects modeling to represent ten-year diameter growth by silvicultural treatment.

Methods

Study Area

The Compartment Study is located on the Big Falls Experimental Forest (BFEF) near Big Falls, MN, USA (48º10'N, 94ºW, 371 m a.s.l.). The study occupies lowland, or peatland, black spruce forest type and is located in block 1 of the BFEF (S25 and S36, T157N, R25W; S11 and S14, T68N, R27W). The climate is continental with short, warm summers and long, cold winters. Maximum summer temperatures can exceed 32 º (90 ºF) with high humidity (80 percent), and minimum winter temperatures can reach -35 ºC (-31 ºF). Precipitation ranges from 500-640 mm (20-25 inches), with average snowfall around 150 cm (50 in).

The BFEF was established in 1948 by an agreement between the Minnesota Department of Conservation (now the Minnesota Department of Natural Resources [MNDNR]) and the USFS Lake States Forest Experiment Station (now the USFS Northern Research Station). The agreement set aside 828 hectares (2,047 acres) of state-owned land for the purpose of silvicultural, harvesting and utilization, and economic studies in lowland conifers (Minnesota Department of Conservation; USDA Forest Service 1948). The management plan for the BFEF outlined several objectives relating to maintaining and improving existing stands of lowland black spruce within the forest. The Compartment Study was implemented to examine the following objectives:

1. To extend the life and productivity of lowland black spruce stands;
2. To improve the growth and yield of black spruce pulpwood;
3. To regenerate cut stands of black spruce;
4. To quicken the rate of production in young stands through forestry operations;
5. To gather information on site conditions and site determination, and;
6. To study the costs and returns of various management practices.

Field Methods

Six silvicultural treatments and a control were implemented in 1948, with each treatment replicated three times, totaling 21 compartments (Table 2.1). Depending upon the treatment, compartments contained eight to 16 permanent 0.405-hectare (0.1 acres) plots and ranged in size from 2.3 to 3.8 hectares (5.8 to 9.5 acres). At the time of establishment, compartments were mostly uneven-aged and ranged in age from 66 to 176 years old. Some compartments contained only a single stand of one condition, while others contained stands of two or three ages and site index values. Site index varied from 9.1 to 18.3 meters in total height at a base age of 100 years.

Silvicultural treatments and measurements were completed between 1948 and 1967 (Table 2.1). Measurements were taken prior to the initial treatments in all compartments between 1948 and 1950. Two additional measurements were taken—one about five years after the initial treatment and another about ten years after the initial treatment (referred to as the "ten-year re-measurement"), just prior to the second treatment. All compartments were treated both initially and at ten years except for the control (which was left untreated) and the light thinning, which only received the initial treatment. Both the measurements and treatments were carried out over two or three seasons (Table 2.1).

Individual tree and plot-level variables were recorded, including species, diameter (all trees over 9.14 cm [3.6 in]), crown class, crown vigor, and form or health descriptions of each tree, and the site index, and age for each plot. On a subset of two to four trees per plot, total height was recorded in one or two measurement years and age was taken via increment core. Individual trees within each plot were stem-mapped, and variables were recorded for specific trees with each measurement. Repeated tree measurements allowed diameter and other variables to be monitored on individual trees over time.

Analysis

Ten-year dbh growth was calculated as the difference between dbh at measurement one (around 1950) and dbh at measurement three (around 1960). Some compartments

Table 2.1. Treatment type and description, measurement and treatment dates, and number of plots and trees in black spruce stands on the Big Falls Experimental Forest in northern Minnesota, USA

Type	Treatment	Description	Measurement Dates			Treatment Dates			
Even-aged	Clear-cut strips	North-south cuts (two to three per compartment); 20-40 m wide beginning from east side; 3 to 4 cuts over 17 years to harvest entire compartment	1950	1956	1960	1950	1961	1964	1967
	Clear-cut patches	Patches of any shape, 0.1 to 0.2 ha in size; 3 to 4 cuts over 17 years to harvest entire compartment	1950	1956	1960	1950	1961	1964	1967
	Shelterwood	Cut from below to ~11.5 m^2 ha^{-1}, leaving strong and vigorous trees; residual stand removed ~10-years later, avoiding damage to understory	1951	1956	1960	1951	1961	NA	NA
Uneven-aged	Group selection	Groups of 4 to 8 trees cut, openings not larger than 9 to 12 m in diameter; develop uneven-aged conditions through variable cutting cycles; entries depending on conditions	1951	1956	1960	1951	1961	NA	NA
	Tree selection	Individual trees of all sizes cut to develop uneven-aged conditions through variable cutting cycles	1951	1956	1960	1951	1961	NA	NA
Intermediate Treatment	Light Thinning	Maintain full canopy while capturing mortality; variable cutting cycle, goal of every 8 to 10 years; regenerate with best method when stand can no longer be thinned	1951	1956	1960	1951	NA	NA	NA

were re-measured at nine or 11 years after the initial measurement. In such instances, ten-year dbh change was standardized by calculating the difference in dbh from measurement one to measurement three, multiplied by ten. Basal area of each plot was summed and expanded to per hectare values.

Crown position was originally assessed on a scale of seven classes: head dominants, strong dominants, conditional dominants and codominants, weak dominants and codominants, intermediates, suppressed trees, and open grown trees. To align with more commonly used crown classes, crown classes were converted to four crown classes often used by using descriptions of the original 7 crown classes in the original working plan (USDA Forest Service 1948),: dominant, codominant, intermediate, and suppressed. Open grown trees were not present in the compartment study.

Diameter growth

Ten-year individual tree diameter growth was analyzed by treatment. An analysis of variance (ANOVA) tested the effect of treatment on individual diameter growth of residual trees. A multiple comparisons test using Bonferonni's p-value was used to determine which treatments varied from one another.

Ten-year diameter growth model

A set of diameter growth models was formulated to predict ten-year diameter change from the initial measurement to the ten-year measurement. Models were adapted and modified from Hann et al. (2003), as it has proven successful in modeling diameter growth in other species (Weiskittel et al. 2007), including black spruce (Subedi and Sharma 2011). The original equation is:

$$\Delta DBH = exp(\beta_0 + \beta_1\, log(DBH + 1) + \beta_2 DBH^2 + \beta_3\, log\left(\frac{UCR+0.2}{1.2}\right) + \beta_4\, log(SI - 4.5) + \beta_5 \frac{BAL^2}{log(DBH+5)} + \beta_6\sqrt{BA} + \beta_7 I_{CR}) + \varepsilon_a \quad (1)$$

where ΔDBH is ten-year diameter increment in cm, DBH is the diameter of the tree at initial measurement, UCR is uncompacted crown ratio, SI is site index (m at 100 years), BAL is basal area in larger trees than the subject tree at the initial measurement, BA is the stand basal area of the initial stand *after* all initial treatments, and ICR is an indicator variable depending on whether crown ratio was measured. B_i' are model coefficients to be estimated, and ε_a is the within-tree error.

Crown ratio was not measured in the compartment study. Instead, the revised four-class crown position variable mentioned above was fit with a dummy variable where dominant and codominant crown classes were given a value of 1, and intermediate and overtopped trees were 0. Predicting crown ratio was considered instead of using a crown position indicator variable, but was ultimately rejected in favor of fitting a model using only data actually measured. Additionally, age was taken at the plot level in the Compartment Study and was assessed as a possible predictor variable.

Model fitting

GNLS Model

Model fitting was completed using R Statistical Software (R Core Team 2017) and the NLME package (Pinheiro et al. 2017). Model fitting began by using only fixed effects as a generalized nonlinear least squares (GNLS) model. Variables were added one at a time from the form suggested by Weiskittel et al. (2007), and were kept in the model by assessing how the variable affected the Akaike information criterion (AIC) value for the model and whether the coefficient for the variable was significant ($p < 0.05$). AIC is defined as $AIC = -2\ \ln(L) + 2k$ where ln is natural logarithm, L is the likelihood function and k is the number of parameters in the model. AIC favors small residual error but penalizes additional predictors that over-fit a model. A variable would stay in the model if the coefficient was significantly different than zero and the AIC of that model was lowered by more than ten points. Model fitting was completed once no additional variables remained, or if additional variables did not meaningfully reduce the AIC. RMSE, mean bias, and the adjusted R^2 value were also assessed to compare model fits.

NLME Model

After the model with only fixed effects was established, random effects using treatment, compartment nested within treatment, and plot nested within compartment nested within treatment were considered as a non-linear mixed effects model (NLME). Taking into account the change from using crown ratio to a crown class dummy variable, this method resulted in a possible model of:

$$\Delta DBH = exp\left(\beta_0 + b_{ijk} + \beta_1\, log(DBH+1) + \beta_2 DBH^2 + \beta_3\, log(SI-4.5) + B_4 Age + \beta_5 \frac{BAL^2}{log(DBH+5)} + \beta_6\sqrt{BA}\right) + \beta_7 CP_{Dummy} + \varepsilon_a \qquad (2)$$

where b_{ijk} is the random intercept term for the *i*th plot in the *j*th compartment in the *k*th treatment and CP is crown position dummy variable (codominants and dominants = 1; intermediate and overtopped = 0). The GNLS and NLME models were compared by assessing difference in AIC of adding random effects, R^2, mean bias and root mean squared error (RMSE) of predicted diameter growth.

As Weiskittel et al. (2007) pointed out, when the assumption of constant variance is violated as it is in these data, a power variance function of the initial diameter can be included which gives less influence to trees with larger initial diameters. This was used in both GNLS and NLME models. The power variance function is defined as $s^2(v) = |v|^{2t}$ where $s^2 v$ is the variance function evaluated at v, v is the variance covariate, and t is the variance function coefficient (Weiskittel et al. 2007; R Core Team 2017).

Deo and Froese Model

The NLME model was also compared to the ten-year diameter growth model for black spruce over 12.7 cm (5 in) dbh developed by Deo & Froese (2013) as a part of their redeveloping the equations for large trees (trees greater than or equal to 12.7 cm dbh) for all Lake States species for use in the Lake States Variant of FVS. The equation defined therein to best model black spruce diameter growth is:

$$\Delta DBH = \beta_0 + \beta_1 \left(\frac{1}{DBH}\right) + \beta_4 \left(\frac{DBH}{QMD5}\right) + \beta_8 CR + \beta_{10} SI \quad (3)$$

where QMD5 is the quadratic mean diameter of all trees greater than 12.7 cm in a plot, β_i are coefficients associated with black spruce based on the dataset used for model fitting by Deo & Froese (2013), and all other variables are as previously defined.

Discrepancies exist over proper coefficients used in the work of Deo & Froese and FVS, however (Smith-Mateja 2018). Therefore, the entire set of predictor variables used by Deo & Froese to model diameter increment for all species considered, and the 'leaps' package (Lumley 2017) was used to select the variables resulting in the best fit model. The potential full model is:

$$\Delta DBH = \beta_0 + \beta_1\left(\frac{1}{DBH}\right) + \beta_2 DBH + \beta_3 + DBH^2 + \beta_4 \frac{DBH}{QMD} + \beta_5 + \frac{DBH^2}{QMD} + \beta_6 BA + \beta_7 BAL + \beta_8 CR + \beta_9 CR^2 + \beta_{10} SI \quad (4)$$

where all variables are as previously defined. In our case, the model was refit across the entire Compartment Study dataset, which includes tree diameters as small as 3.6" instead of the 5.0" dbh minimum used in the original modeling by Deo & Froese. To overcome crown ratio not being measured in the Compartment Study, crown ratios using the equation in FVS described by Dixon and Keyser (2017) were calculated using the equation:

$$UCR = 10 * \left(\left(\frac{\beta_1}{1+\beta_2 BA}\right) + \beta_3\left(1 - exp(\beta_4 DBH)\right)\right) \quad (5)$$

where β_i are coefficients specific to black spruce, BA is basal area in $ft^2\ ac^{-1}$, and DBH is dbh in inches.

The full range of diameters were used in comparing model performance when comparing the GNLS, NLME and refit Deo & Froese models. Fit statistics (RMSE and mean bias) were compared to assess the better fitting model. While the equations for other species have been implemented into FVS, the black spruce equation has yet to be implemented. Therefore, comparisons will be made to the refit Deo & Froese model and referred to as such rather than the FVS model.

Results

Diameter growth

A large range of both stand conditions—both before (Tables 2.2 and 2.3) and after (Table 2.4) initial treatment—and tree conditions (Table 2.5) existed in each treatment. Significant treatment effects were found on 10-year diameter growth (p <0.001), with the greatest growth in the shelterwood treatment at nearly 2.4 cm (SD = 0.98 cm; Figure 2-1). The individual tree selection (mean = 1.8 cm, SD = 0.79 cm) and group selection (mean = 1.8 cm, SD = 0.71 cm) methods saw the next greatest growth, significantly higher than the remaining methods. The thinning (mean = 1.5 cm, SD = 0.63 cm) was the only other treatment to experience significantly higher growth than the control, with the clear-cut strips and clear-cut patches not resulting in significant differences (p>0.05).

Ten-year diameter growth model

Model fitting for the GNLS and NLME models resulted in six fixed effects (equation 6). The GNLS model fitting began with predicting diameter change by initial DBH (AIC: 22,266, p-value: <0.05), adding SI (AIC:22,156, p-value <0.05), and adding $\sqrt{SBA}$ (AIC: 20,993, p-value: <0.05). The next variable tested was stand age (AIC: 20,984, p-value: 0.0014). Though it was a significant predictor, it did not greatly reduce the AIC from the previous model and was removed. Then, the first variable (dbh) was changed to the $log(\ DBH)$ to reflect Hann (2003), which improved the model fit (AIC: 20,892, p-value <0.05). Three additional variables were added sequentially, which improved model fit: DBH^2 (AIC: 20,636, p-value <0.05), $\frac{BAL^2}{log(DBH+5)}$ (AIC: 20,517, p-value: <0.05), and CP_{Dummy} (AIC: 20,360, p- value: <0.05).

$$\varDelta DBH = exp\left(\beta_0 + \beta_1 \, log(DBH+1) + \beta_2 DBH^2 + \beta_3 \, log(SI - 1.37) + \beta_5 \frac{BAL^2}{log(DBH+5)} + \beta_6\sqrt{BA} + CP_{Dummy}\beta_7 \right) + \varepsilon_a \qquad (6)$$

Table 2.2. Mean, standard deviation, and range of site index and age in six silvicultural treatments and the control in 1948 on the Big Falls Experimental Forest in northern Minnesota, USA

Treatment	n plots	Site index (Ht in m at 100 yrs)			Age (yrs)		
		Mean	SD	Range	Mean	SD	Range
Thinning	26	12.8	2.1	9.1-15.2	140.0	37.9	90-180
Shelterwood	30	16.2	1.5	15.2-18.3	113.3	36.5	70-160
CC strips	48	13.6	2.4	9.1-18.3	134.6	14.3	100-150
CC patches	43	12.8	1.5	9.1-15.2	119.1	44.0	70-180
Group sel.	37	15.0	1.3	12.2-18.3	98.4	33.9	70-180
Tree sel.	30	13.4	2.0	9.1-15.2	117.3	27.3	70-150
Control	23	13.1	2.8	9.1-18.3	106.1	27.3	70-130

Table 2.3. Mean, standard deviation, and range of pre-treatment density measures (basal area ha and trees ha) in six silvicultural treatments and the control in 1948 on the Big Falls Experimental Forest in northern Minnesota, USA

Treatment	n plots	Basal area (m^2 ha^{-1})			Trees (Trees ha^{-1})		
		Mean	SD	Range	Mean	SD	Range
Thinning	26	30.3	4.4	21.5-36.6	2125	456.4	1334-3163
Shelterwood	30	30.0	4.7	17.6-38.0	1613	426.5	618-2446
CC strips	48	28.6	6.0	12.5-39.0	1725	524.6	717-2866
CC patches	43	27.4	5.9	16.3-37.5	1927	423.0	988-2496
Group sel.	37	30.5	5.6	16.0-38.6	1921	428.0	840-2669
Tree sel.	30	27.2	6.4	15.4-39.9	1753	526.8	642-2916
Control	23	25.8	6.5	10.7-33.7	1780	381.3	1013-2570

Table 2.4. Mean, standard deviation, and range of stand conditions after initial treatment in each silvicultural treatment in 1950 of plots used in a ten-year diameter growth model on the Big Falls Experimental Forest in northern Minnesota, USA

Treatment	n		Basal area (m^2 ha^{-1})			Trees (Trees ha^{-1})		
	Plots	Trees	Mean	SD	Range	Mean	SD	Range
Thinning	26	1,425	21.9	2.9	16.3-26.5	1443	277.3	964-2026
Shelterwood	30	423	11.8	2.5	6.9-17.4	493	105.0	297-717
CC strips	37	2,396	28.0	6.2	12.5-39.0	1718	566.6	717-2866
CC patches	27	1,997	28.1	5.3	17.9-37.5	1920	435.9	988-2496
Group sel.	25	1,161	20.1	3.4	13.0-27.2	1247	286.6	667-1705
Tree sel.	30	1,254	17.5	5.1	9.8-32.4	1111	336.8	395-1680
Control	23	1,580	25.8	6.5	11.4-33.7	1780	381.3	1013-2570

Table 2.5. Mean, range, and standard deviation of variables for the diameter growth model of all trees in the dataset (9.1 cm and greater)

Variable	N	Mean	SD	Range
Tree	10,231			
DBH (cm)		13.7	3.3	9.1-32.5
BAL (m^2 ha^{-1})		14.8	8.3	0-38.8
CPd		0.700	0.459	0-1
0	3,079			
1	7,157			
Plot	198			
SI (m at 100-years)		13.8	2.29	9.1-18.3
BA (m^2 $acre^{-1}$)		21.9	7.45	30.2-170.0

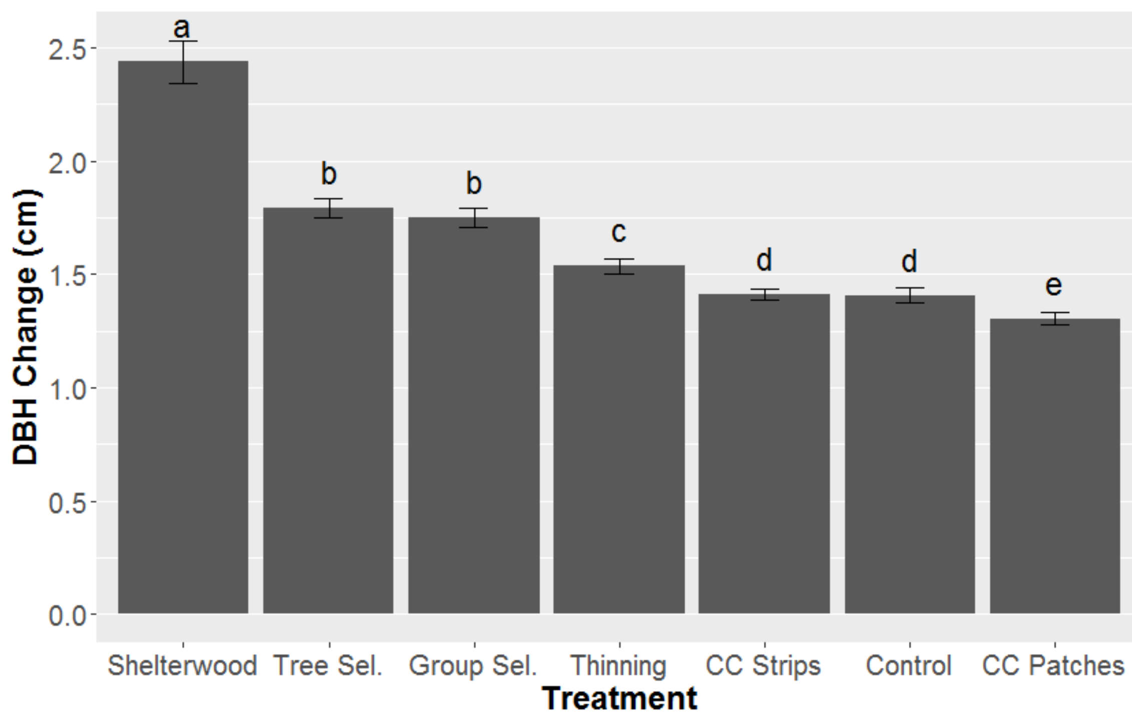

Figure 2-1. Average diameter growth of residual trees by treatment on the Big Falls Experimental Forest in northern Minnesota, USA. Error bars indicate standard errors

After fitting the GNLS model, nested random effects were added in fitting the NLME model. First, a random effect of treatment was tested which improved the model fit (AIC: 20,257). Compartment nested within treatment greatly reduced the AIC (19,752). Plot nested within compartment nested within treatment further improved model fit (AIC: 19,258) and resulted in the best NLME model (equation 7). The final NLME model improved the coefficient of determination from 0.2056 to 0.3114 over the GNLS model. The RMSE decreased from 0.6772 to 0.6104 cm. Fit statistics for the final ten-year diameter growth models are in Tables 2.7 and 2.8. Parameter estimates and their standard errors are in Table 2.6. The final mixed effects model form is:

$$\Delta DBH = exp\left(\beta_0 + b_{ijk}\beta_1 \, log(DBH+1) + \beta_2 DBH^2 + \beta_3 \, log(SI - 1.37) + \beta_5 \frac{BAL^2}{log(DBH+5)} + \beta_6\sqrt{BA} + CP\beta_7\right) + \varepsilon_a \tag{7}$$

where b_{ijk} is a unique intercept term added to β_0 for each plot.

The signs and values for both the GNLS and NLME models matched biological expectations for diameter growth. Positive coefficients occurred with log(dbh+1), log(SI-1.37), and the crown position dummy variable, indicating diameter growth was positively correlated with these variables. Diameter growth was negatively correlated with $BA^{1/2}$, dbh^2, and $\frac{BAL^2}{\log(DBH+5)}$. Notably, dbh growth is strongly positively correlated with log(dbh+1) but negatively correlated with dbh^2, showing that black spruce individuals with particularly large initial diameters will grow more slowly than trees with smaller diameters. This is evidenced when plotting diameter growth in normal stand conditions using the NLME parameters (Figure 2-2).

Table 2.6. Parameter estimates and standard errors for the GNLS and NLME models predicting ten-year diameter growth in lowland black spruce on the Big Falls Experimental Forest in northern Minnesota, USA

Parameter	Associated term	GNLS		NLME	
		Coef.	SE	Coef.	SE
B_0		-1.6827	0.1885	-0.6041	0.2558
B_1	log(DBH +1)	0.7777	0.0869	0.0367	0.0865
B_2	log(SI – 4.5)	0.4444	0.0237	0.0361	0.0703
B_3	$BA^{1/2}$	-0.1656	0.0075	-0.1303	0.0225
B_4	DBH^2	-0.0015	0.0002	-0.0012	0.0002
B_5	$BAL^2 (\log(DBH + 5)^{-1}$	-0.0007	0.0001	-0.0011	0.0001
B_6	CPd	0.1587	0.0126	0.2047	0.0122

Table 2.7. Fit statistics (RMSE and mean bias) and predicted and observed ten-year diameter change values by treatment for the NLME and re-fitted Deo & Froese (2013) ten-year diameter growth models for black spruce

Treatment	RMSE (cm)		Mean bias (cm)		Ten-year DBH change (cm)		
	NLME	Deo & Froese	NLME	Deo & Froese	Observed	NLME	Deo & Froese
All treatments	0.6104	0.6849	0.0054	-0.1469	1.536	1.539	1.357
Shelterwood	0.8345	0.9853	0.0047	-0.3036	2.438	2.449	2.141
Tree sel.	0.6807	0.7884	-0.0074	-0.2310	1.790	1.789	1.565
Group sel.	0.6547	0.7121	-0.0018	-0.1445	1.751	1.752	1.609
Thinning	0.5697	0.5983	-0.0437	-0.1305	1.536	1.543	1.456
CC strips	0.5932	0.6750	0.0046	-0.2399	1.413	1.414	1.170
CC patches	0.5490	0.6127	0.0083	-0.1319	1.307	1.312	1.171
Control	0.5804	0.6514	0.0632	-0.1271	1.410	1.415	1.225

Table 2.8. Fit statistics for the GNLS and NLME equations (Akaike Information Criterion and adjusted R2) and model performance for the GNLS, NLME, and re-fitted Deo & Froese (2013) equations predicting ten-year diameter growth of black spruce

Formula	AIC	R^2	RMSE (cm)
GNLS	20,360	0.2047	0.6772
NLME	19,258	0.3113	0.6104
Deo & Froese		0.1352	0.6849

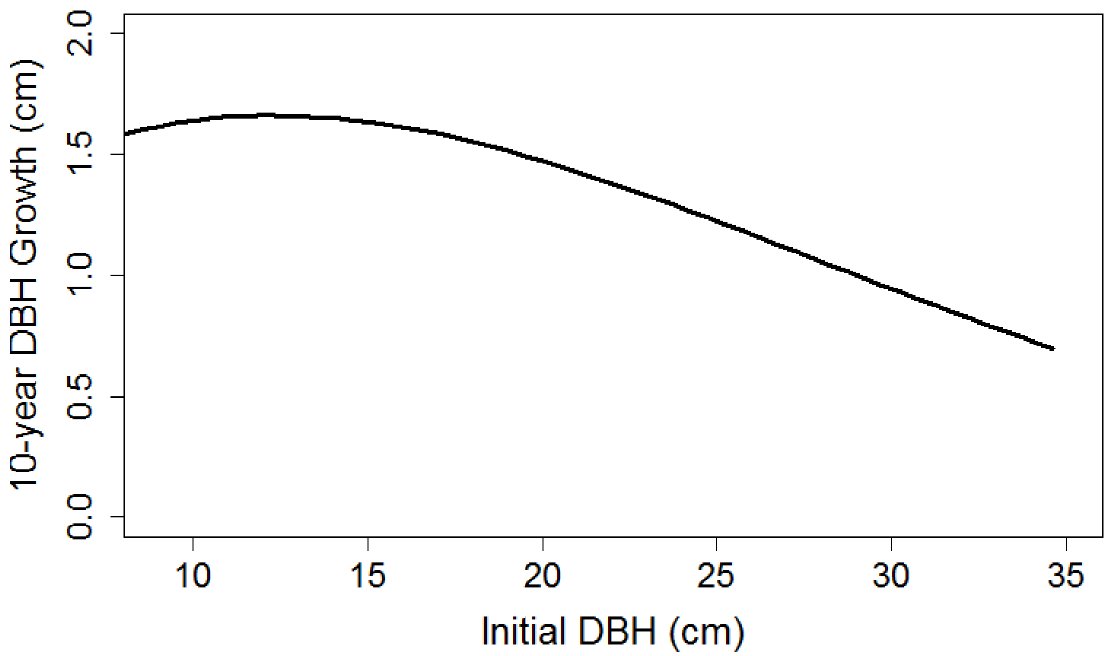

Figure 2-2. Diameter growth using NLME coefficients in normal stand conditions (Basal area=22.0 m2 ha-1, basal area in larger trees=14.8 m2 ha-1, site index=13.3 m at 100 yrs, crown position dummy variable=0.6992).

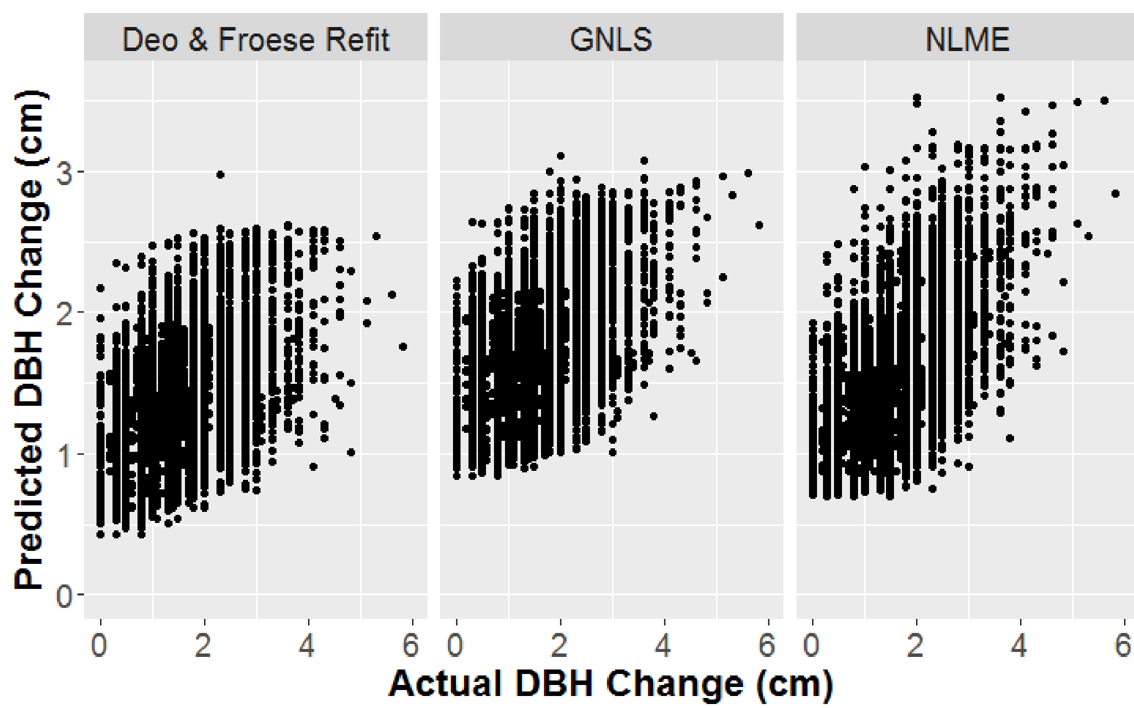

Figure 2-3. Actual DBH change versus fitted DBH change for all three models predicting 10-year diameter change in lowland black spruce in northern Minnesota.

Refitting the model of Deo & Froese resulted in all but two of their independent variables being used to predict diameter increment (Equation 7). $\frac{\text{dbh}}{\text{QMD}}$ and $\frac{\text{dbh}^2}{\text{QMD}}$ were the two variables that fell out.

$$\Delta DBH = \beta_0 + \beta_1\left(\frac{1}{DBH}\right) + \beta_2 DBH + \beta_3 + DBH^2 + \beta_6 BA + \beta_7 BAL + \beta_8 CR +$$

$$\beta_9 CR^2 + \beta_{10} SI \qquad (7)$$

The NLME model outperformed the model by Deo & Froese, resulting in a higher adjusted R^2 value (0.3113 vs. 0.1352) and a lower RMSE (0.6104 vs. 0.6849). The GNLS model saw mixed results, with an adjusted R^2 value of 0.2047 and a lower RMSE than the refit Deo & Froese model (06773). The NLME model was much better in predicting diameter growth over the refit Deo & Froese model across all treatments (Table 2.7). The overall mean bias of the NLME model was 0.0054 cm compared with -0.1469 cm for the Deo & Froese refit model. The Deo & Froese refit model underestimated diameter growth consistently across all treatments (Figure 2-3). The NLME model predicted average diameter growth was nearly identical to the observed growth, at 1.536 compared to 1.539 cm over ten years, while the Deo & Froese refit model averaged 1.357 cm (Table 2-7).

Discussion

The shelterwood treatment experienced the greatest diameter growth compared to the other treatments, and its growth was significantly increased over the control (Figure 2-1). The shelterwood treatment also had the least amount of residual BA and lowest residual TPA of all treatments (Table 2.4). The higher intensity of cutting resulted in greater growing space for residual trees in this treatment. The selection methods had the next highest average diameter growth, and correspondingly had the next lowest residual BA. This pattern continues for the thinning treatments. Notably, plots that were re-measured in 1960 in the clear-cut methods were those not yet harvested. Plots in patches or strips that were harvested were not re-measured due to the immature size class of regeneration. There was not significantly more growth in residual plots in these clear-cut methods, even though stand removal in the form of clear-cut strips or patches may have been as close as 15 meters based on visual evidence of treatments and the cutting cycles of the experiment (Figure 2-4).

Fitting the diameter growth model by adapting the model of Hann (2003) and manually adding variables resulted in favorable fit statistics (Table 2.7). It was successful in that the equation form was as simple as possible using two frameworks: 1.) by first adding basic variables (e.g., initial diameter), next adding more complex variables (e.g., $\frac{BAL^2}{\log(DBH+5)}$), and finally changing the simple variables added first to more complex variables (e.g., changing initial diameter to log(dbh+1)), and; 2.) by using AIC to balance model performance with model complexity. Using the power variance structure by weighting the variance for trees with larger diameters was effective in overcoming non-constant variance to reduce the bias introduced by large trees. Age was tested as a possible independent variable but was not meaningful. Age was not a factor in previous fittings using this model (Hann et al. 2003; Weiskittel et al. 2007) or in Subedi and Sharma's (2011) model fitting for black spruce. Including age as a predictor variable may also limit the model's applicability to stands where age is not measured or stands are uneven-aged.

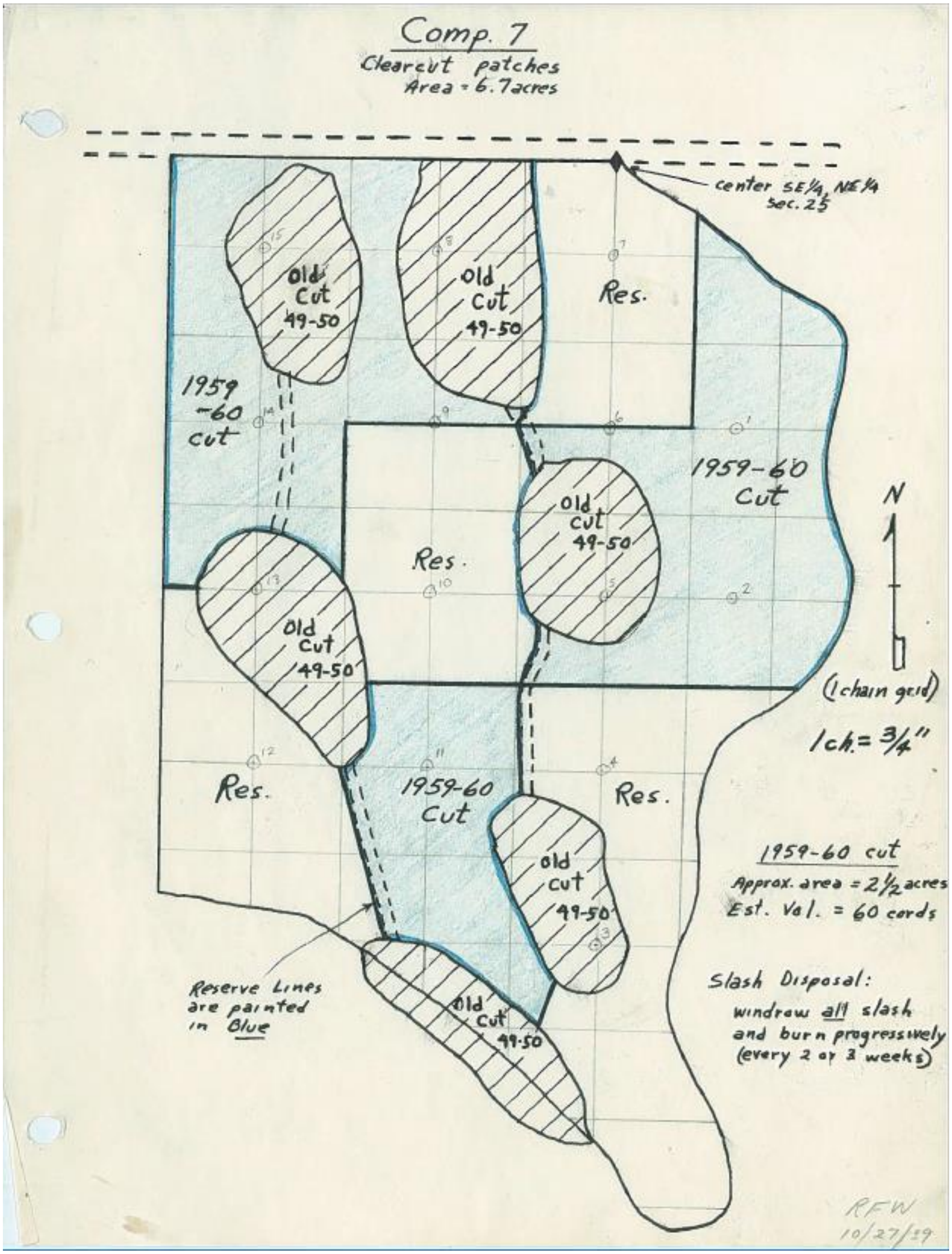

Figure 2-4. A map showing plot locations and years of cuts of a clear-cut patch treatment in the Compartment Study on the Big Falls Experimental Forest in northern Minnesota, USA. Map courtesy of USDA Forest Service documents.

Adding random effects (NLME) after fitting the model with all fixed effects (GNLS) was successful in improving model performance. The method of first adding treatment, then compartment nested within treatment, and finally plot nested within compartment nested within treatment was logical by slowly increasing complexity. Adding both treatment and compartment nested within treatment improved model performance; however, adding plot to the nested random effect increased the AIC value, suggesting that plot level effects outside of those incorporated in the model (BA and SI) did not help explain the variability in ten-year diameter growth. Adding compartment as a nested random effect with treatment was particularly effective in improving model performance. Compartments ranged in size from 2.3 to 3.8 hectares (5.8 to 9.5 acres) and were located within about two kilometers (1 mile) of one another. However, site characteristics can change even in short distances in black spruce peatlands. Site and environmental factors that were not measured such as peat depth, water table level, soil moisture, or pH may help explain additional variability not captured in the model.

This modeling approach fit a single growth model to all diameters in the dataset (9.1-32.5 cm). The work by Deo & Froese (2013) refit the large tree diameter growth equations (trees greater than 9.1 cm) used in the Lake States Variant of FVS. FVS models diameter growth differently for large and small trees (those below 9.1 cm dbh, and those equal to or greater than 9.1 cm). Fitting a single growth model for black spruce and other slow-growing species that attain smaller diameters may be advantageous over the current approach in FVS. The diameter growth curve (Figure 2-2) under average stand conditions shows that diameter growth in peatland black spruce peaks around 12.7 cm. Since black spruce grows under a variety of site conditions and maximum sizes vary largely depending on those conditions, having separate equations for small and large trees with a transition near the peak of diameter growth for a species may not be ideal. Additionally, FVS diameter increment models for large and small trees were originally developed for the Intermountain West where average and maximum diameters for tree species are generally greater than Lake States species. Fitting separate equations with a breakpoint diameter of 12.7 cm in those geographic regions may be more appropriate than in the Lake States, particularly for species with smaller maximum diameters like black spruce.

Model fitting resulted in the same variables predicting diameter growth as was found with the same model for other species by Hann (2003) and Weiskittel et al. (2007). The substitution of a crown position indicator variable (1 for dominant and codominant, 0 for intermediate and suppressed) for crown ratios seems adequate given that crown ratio was not measured in the original study. This may provide an alternative variable to crown ratio that is less time consuming to measure in the field, particularly in black spruce where visibility in the canopy can be low due to dense crowns.

Growth models are an important tool in managed forests of any cover type. Understanding how silvicultural systems and stand- and tree-level attributes affect diameter growth in geographical locations and physiological conditions is critical for accurately modeling future stand conditions and volumes. Black spruce growing conditions vary widely depending on its location and proximity to its range edges (Viereck and Johnston 1990). Therefore, it is important that diameter growth models applicable to conditions in the Lake States be used where black spruce tends to grow in pure stands on lowland sites. Similarly, the application of management recommendations in black spruce from the results of silvicultural studies should come from similar site conditions. This study helps fill a large gap in recent research studying lowland black spruce silviculture and diameter growth models in the Lake States.

Conclusion

Fitting ten-year diameter growth equations using the equation presented by Hann (2003) proved successful in lowland black spruce. Treatment did not have an effect on model performance, and the fitted model did very well in predicting diameter growth across the breadth of silvicultural treatments in the Compartment Study. Fitting a diameter increment model across a wider range of diameters in black spruce seems effective, and may be an important alternative to current procedures in FVS where two separate diameter growth models are used at at the transition oint where black spruce diameter growth peaks. A shelterwood system may be applicable in black spruce systems when land managers are hoping to quickly increase the size of residual trees prior to an overstory removal cut. Care must be taken to when considering the residual BA as black spruce's susceptibility to wind-throw and wind-breakage can cause great losses. Selection methods may be viable alternatives to even-aged clear-cutting methods where land managers have the resources to make multiple entries.

Chapter 3 Quantifying short- and long-term effects on individual tree and stand structure and composition dynamics

Introduction

Black spruce (*Picea mariana* (Miller) B.S.P.) is distributed broadly across North American boreal forests and is an important species both economically and ecologically (Viereck and Johnston 1990). Black spruce is the most important pulpwood species in Canada, and is an important commercial species in the Lake States region (Michigan, Minnesota, Wisconsin) of the United States (Viereck and Johnston 1990). In Minnesota, black spruce comprises 648,000 hectares (1.6 million acres) of the 7.04 million forested hectares (17.4 million acres) (Miles 2017) and is the second-most harvested pulpwood species by volume (Minnesota Department of Natural Resources 2017). Black spruce forest types constitute important habitat for many species, including snowshoe hare (*Lepus americanus* Erxleben, 1777), spruce grouse (*Falcipennis canadensis* (Linnaeus, 1758)), American marten (*Martes Americana* (Turton, 1806)), salamanders (Salamandridae family), cavity-nesting birds, and other small mammals (Cimon-Morin et al. 2010).

Black spruce stands typically grow on wet organic soils in lowland forests, but upland stands on mineral soils also occur, particularly in central Canada (Viereck and Johnston 1990). Peatland stands in the Lake States are typically composed of almost entirely black spruce, but can be mixed with tamarack (*Larix laricina* (Du Roi) K. Koch), and to a lesser degree northern white-cedar (*Thuja occidentalis* L.), balsam fir (*Abies balsamea* (L.) Miller), white spruce (*Picea glauca* (Moench) Voss), paper birch (*Betula papyrifera* Marshall), and red maple (*Acer rubrum* L.) (Viereck and Johnston 1990).

The successional dynamics of black spruce forests in northern Minnesota are shaped by both infrequent stand replacing disturbances (i.e., fire return interval of 700 to 100 years) and smaller scale gap dynamics (Aaeseng et al. 2003). Infrequent, high intensity stand-replacing fires result in mostly even-aged black spruce stands. As stands age, gaps form due to smaller-scale disturbances such as wind, disease, insect outbreaks, and mortality due to age or suppression (Johnston and Smith 1983). Advance regeneration and vegetative reproduction from layering take advantage of open growing space to form uneven-aged stand conditions (Viereck and Johnston 1990). Stands may also transition with age from purely black spruce to a mix of tamarack, northern white-cedar, balsam fir, white spruce, and paper birch (Viereck and Johnston 1990). Black spruce has semi-serotinous cones, which allow extensive amounts of seed to disperse following fire. However, seed dispersal is fairly routine in stands over 40 years old, as new seed is produced in most years with heavier seed crops every two to six years (Johnston 1977a). Seed dispersal distance is effective up to 80 meters (260 feet) from the windward side of residual stands (Johnston 1977a).

Forest managers have traditionally managed black spruce stands using even-aged systems, particularly clearcutting methods (Viereck and Johnston 1990; Youngblood and Titus 1996). Traditional clearcutting has often been followed by a combination of prescribed fire to improve seedbed conditions (Johnston 1977a) or scarification (Kolabinski 1991) and subsequent aerial seeding to facilitate artificial regeneration (Weetman 1975; Johnston 1977a; Groot 2002). Prescribed fire is now used less frequently due to increasing costs, the growing wildland-urban interface, and logistical difficulties.

Strip clear-cuts and patch clear-cuts are alternatives that may promote natural regeneration due to narrow cuts taking advantage of natural seeding.

In Ontario and Quebec, Canada, alternative silvicultural systems have been explored. Harvest systems that take advantage of advance regeneration are widely used (Groot and Hökkä 2000). Shelterwood systems are suggested where uneven-aged stands have formed and advance regeneration is already present, and have been adopted in Quebec when such stand conditions exist (Groot 2002; Groot et al. 2005). Groot et al. (2005) note that in older stands where advance regeneration exists, advances in logging equipment have made practices like the one termed "Careful Logging Around Advance Growth" (CLAAG) feasible to protect regeneration. Another form of retaining advance regeneration is harvesting with advance regeneration present (HARP), which was used in northeastern Ontario in combination with strip clear-cuts (Deans et al. 2003). In residual uncut strips, a diameter limit cut was used to thin stands. This study also suggested a HARP system aided the retention and redevelopment of features common in lowland black spruce forests. Thinning as an intermediate treatment has been shown to increase net merchantable volume by up to 33% over unthinned stands after 15 years (Soucy et al. 2012) and improve post-treatment radial growth by 20 to 100 percent over pre-treatment growth (Vincent et al. 2009).

Uneven-aged silvicultural systems have also been recommended under certain conditions. In Minnesota in particular, uneven-aged methods were used in the mid- to late-20th century. Group or individual tree selection methods have been suggested in stands on poor sites where layering is common (Heinselman 1959; Johnston and Smith 1983). While partial cutting has increased diameter growth in both even and uneven-aged stands, diameter growth is less uniform in uneven-aged stands due to the variability in stand density (Pamerleau-Couture et al. 2015). Partial selection cuts have been shown to result in slow understory growth of black spruce in Minnesota (Heinselman 1959), and concerns exist about its profitability (Groot 2002).

Additionally, concerns exist in Minnesota over the age of the resource and the widespread problems caused by eastern spruce dwarf mistletoe (*Arceuthobium pusillum*). Sixty-six percent of Minnesota's black spruce resource, or 421,000 hectares (1.04 million acres), is 60 years of age or older, with only 6% under 40 years of age (Miles 2017). Dwarf mistletoe is a parasitic plant that forms witches brooms in black spruce, reducing growth and eventually killing infected trees. It is estimated that 11% to 55% of black spruce stands in Minnesota are infected (Baker et al. 2012). Management recommendations call for clear-cutting infected stands with a buffer strip of up to 40 meters around infections to ensure latent infections are completely removed (Johnston 1977a; Baker et al. 2006).

There are few studies in lowland black spruce that describe the effects of a variety of silvicultural treatments over the last 50 years in the Lake States. In particular, long-term studies on stand structure are needed to understand the effects of silviculture practices in black spruce (Groot et al. 2005). Additionally, interpretations of the effects of alternative silvicultural treatments in black spruce stands infected with mistletoe are limited. This study aims to help fill the gap in understanding the effects and applicability of alternative silvicultural systems in lowland black spruce stands in the Lake States in a variety of stand conditions. The objective is to quantify the short- and long-term effects of six silvicultural methods on individual tree (e.g., diameter growth) and stand-level attributes (e.g., basal area growth, mortality, stand structure, stand composition measures, and deadwood).

Methods

Study Area

This work tool place in “The Compartment Study” on the Big Falls Experimental Forest (BFEF) in northern Minnesota, USA near Big Falls (48º10’N, 94ºW, 1,217 ft a.s.l.). The study area is lowland, or peatland, black spruce forest type and is located in block 1 of the BFEF (S25 and S36, T157N, R25W; S11 and S14, T68N, R27W). The climate is continental with short, warm summers and long, cold winters. Maximum summer temperatures can exceed 32 ºC (90 ºF) with high humidity (80 percent), and minimum winter temperatures can reach -35 ºC (-31 ºF.) Precipitation ranges from 500-640 mm (20-25 in), with average snowfall around 152 cm (60 in).

The BFEF was established in 1948 by an agreement between the Minnesota Department of Conservation (now the Minnesota Department of Natural Resources [MNDNR]) and the USFS Lake States Forest Experiment Station (now the USFS Northern Research Station). The agreement set aside 828 hectares (2,047 acres) of state-owned land for the purpose of silvicultural, harvesting and utilization, and economic studies in lowland conifers (Minnesota Department of Conservation; USDA Forest Service 1948). The management plan for the BFEF outlined several objectives relating to maintaining and improving existing stands of lowland black spruce within the forest. While this chapter does not specifically focus any of the objectives specifically, the Compartment Study was implemented to examine the following objectives:

1. To extend the life and productivity of lowland black spruce stands;

2. To improve the growth and yield of black spruce pulpwood;

3. To regenerate cut stands of black spruce;

4. To quicken the rate of production in young stands through forestry operations;

5. To gather information on site conditions and site determination, and;

6. To study the costs and returns of various management practices.

Field Methods

Six silvicultural treatments and a control were implemented around 1950, with each treatment replicated three times totaling 21 compartments (Table 3.1). Treatments included three even-aged methods, two even-aged methods, and an intermediate treatment. The three uneven-aged methods were clear-cut strips and clear-cut patches (3-4 entries over 16 years to harvest the stand; strips up to 20 m wide, patches up to 40 m wide) and a shelterwood (shelterwood cut to about 12 m^2 ha^{-1}, leaving evenly-spaced good-risk trees; overstory removed 10-11 years later). The two uneven-aged methods were group and tree selection (cut individual or groups of 4-8 trees, maintaining a well-stocked stand in order to develop all-aged conditions). The intermediate treatment as a thinning (salvaging mortality and provide growing space for residual trees).

Compartments ranged in size from 2.3 to 3.8 hectares (5.8 to 9.5 acres). At the time of establishment, compartments were largely uneven-aged, ranging from 66 to 176 years old. Most compartments contained only a single stand of one condition, while others contained stands of two or three ages and site index values. Site index was measured at a base age of 100 years, likely due to the slow growth of black spruce, and varied from 9.1 to 18.3 meters in total height (Table 3.1).

A series of treatments and measurements was carried out between 1948 and 1967 (Table 3.1). Measurements were taken prior to the initial treatments in all compartments between 1948 and 1950. Two additional measurements were taken—one about five years after the initial treatment and another about ten years after the initial treatment (referred to as the "ten-year re-measurement") and just prior to the second treatment. All compartments were treated both initially and at ten years except for the control and the light thinning, which only received the initial treatment. Both the measurements and treatments were carried out over two seasons due to the size of compartments and number of replicates, but the year each was completed is reported in Table 3.1.

Depending upon the treatment, compartments contained eight to 16 permanent 0.405-hectare (0.1 acres) plots. Measurements were collected on trees 9.144 cm (3.6 in) and greater in diameter. Individual tree measurements taken were species, diameter, crown class, crown vigor, and form or health descriptions of each tree. Plot level measurements taken were site index, and age for each plot (Table 3.2). On a subset of two to four trees per plot, total height was recorded in one or two measurement years and age was taken via increment core. Individual trees within each plot were stem-mapped, and variables tracked for each tree over the initial 1950-1960 measurements. Additionally, 0.00404686 ha plots nested within the larger plots with the same plot center were measured to assess regeneration. All stems of woody species less than 9.144 cm were tallied by species.

In summer 2017, a subset of compartments were re-measured. After the study was declared closed in 1977 (Johnston 1977b), regeneration harvests unassociated with the study occurred in 60% or more of the compartments. Two compartments of each of the clear-cut strips, clear-cut patches, and shelterwood treatments were at least partially intact and re-measured. A large proportion of plot center posts were relocated from the original study. Original stand maps denoted the distance between plots. Where plot centers could not be found, the distance from located plot centers to missing plot centers was measured and the plot was re-established. Although the re-established plots may not contain the exact plot area in all cases, we are confident that they do represent the plot conditions. The shelterwood treatment had 17 out of 30 intact plots, the clear-cut strips treatment had 29 out of 48, and the clear-cut patches treatment had 32 out of 43.

Due to the types of treatments (regeneration harvest) and the reestablishment of a subset of the plots, individual tree measurements were not paired with 1950s measurements. Variables re-measured were largely the same (Table 3.1). Crown vigor was not recorded due to the inherent bias of multiple field technicians estimating vigor. Total height and height to live crown were measured on a subset of three trees per plot.

To measure the importance of standing and downed deadwood in stands, two forms of deadwood measurements were taken: dbh of all standing dead trees, and coarse woody debris (CWD) on the forest floor. The procedure for measuring CWD followed that outlined by the USDA Forest Service for the Forest Inventory and Analysis (FIA) program (USDA Forest Service 2011). On every plot, one transect at a random azimuth intersecting the plot center was run across the entire plot diameter (22.68 m). Deadwood on the forest floor that intersected the transect was measured if it met criteria for each ascribed decay class. For decay classes 1 to 4, a piece was tallied and its diameter at the intersection and length from its large end to a minimum diameter of 7.6 cm (3.0 in) was recorded if its diameter at the point of intersection was 7.6 cm or greater and its length was at least 0.914 m (3.0 ft). A piece in decay class 5 was measured if its diameter was at least 12.7 cm (5.0

Table 3.1. Treatment type and description, measurement and treatment dates, and number of plots and trees in black spruce stands on the Big Falls Experimental Forest in northern Minnesota, USA

Type	Treatment	Description	Measurement Dates				Treatment Dates			
Even-aged	Clear-cut strips	North-south cuts (two to three per compartment); 20-40 m wide beginning from east side; 3 to 4 cuts over 17 years to harvest entire compartment	1950	1956	1960	2017	1950	1961	1964	1967
	Clear-cut patches	Patches of any shape, 0.1 to 0.2 ha in size; 3 to 4 cuts over 17 years to harvest entire compartment	1950	1956	1960	2017	1950	1961	1964	1967
	Shelterwood	Cut from below to ~11.5 m^2 ha^{-1}, leaving strong and vigorous trees; residual stand removed ~10-years later, avoiding damage to understory	1951	1956	1960	2017	1951	1961	NA	NA
Uneven-aged	Group selection	Groups of 4 to 8 trees cut, openings not larger than 9 to 12 m in diameter; develop uneven-aged conditions through variable cutting cycles; entries depending on conditions	1951	1956	1960	-	1951	1961	NA	NA
	Tree selection	Individual trees of all sizes cut to develop uneven-aged conditions through variable cutting cycles	1951	1956	1960	-	1951	1961	NA	NA
Intermediate	Light thinning	Maintain full canopy while capturing mortality; variable cutting cycle, goal of every 8 to 10 years; regenerate with best method when stand can no longer be thinned	1951	1956	1960	-	1951	NA	NA	NA

Table 3.2. Tree and plot-level variables taken in the original set of measurements and the 2017 measurement in the Compartment Study, Big Falls Experimental Forest in northern Minnesota, USA.

Variable	Variable measured by year	
	1950s	2017
Species	Yes	Yes
DBH (live & dead trees)	Yes	Yes
Crown position	Yes	Yes
Crown vigor	Yes	No
Health/form concerns	Yes	Yes
Cause of mortality (if applicable)	Yes	Yes
Height	Yes[1]	Yes[2]
Height to live crown	No	Yes[2]
Age	Yes[1]	No
Coarse woody debris	No	Yes

1: Measured on a subset of 2-4 trees per plot
2: Measured on a subset of 3 trees per plot

in). A decay class was assigned for each piece ranging from 1 to 5 depending on its decay condition, where:

$$DC = decay\ class \begin{cases} 1 = sound; no\ decay \\ 2 = sound; sapwood\ beginning\ to\ decay \\ 3 = sound\ \ heartwood; decayed\ sapwood \\ 4 = decayed\ heartwood \\ 5 = no\ structure; soft\ and\ powdery \end{cases}$$

Dead trees and tall stumps that were leaning greater than 45 degrees from vertical that met the criteria were counted as CWD and measured accordingly.

Analysis

Short-term analysis

To assess the effects of all six treatments over the short term at the stand level, a number of stand-level metrics were assessed. The ten-year analysis assessed differences in individual tree diameter growth and basal area per hectare change in the residual (uncut) stand, and individual tree mortality. Basal area change is based only on plots that were not completely or partially harvested in the first treatment. Plots in the clear-cut patches or clear-cut strips treatments that were cut completely were not a part of the residual stand and were left out of calculating treatment average basal area. Average mortality by treatment was calculated and assessed for differences between treatments. Mortality was calculated by plot as a percent by dividing the total number of dead trees in the 10-year measurement that were present and not harvested in the initial measurement.

Long-term analysis

Density

Two common measures of stand density were assessed to determine differences among treatments: trees per hectare and basal area per hectare.

Structural complexity

Stand structure was evaluated using several common stand-level measurements and additional metrics to quantify structural complexity and heterogeneity in the various treatments. At the individual tree level, Average dbh, total height, and uncompacted live crown ratio (UCR) were assessed to quantify treatment differences. UCR is defined as

$$UCR = \frac{Ht - HCB}{Ht}$$

where Ht is the total height of the tree and HCB is the height to the base of the crown. A higher ratio corresponds to higher proportion of the tree being occupied by branches with live foliage, which equates to greater vertical structure.

Additionally, the Gini coefficient was calculated for each plot as a measure of tree size inequality using the form suggested by D’Amato et al. (2011) as:

$$Gini_{DBH} = \frac{\sum_{i=1}^{n}(2i - n - 1)x}{n^2\mu}$$

where i is a tree number assigned from a tree list ordered by ascending dbh, n is the number of trees in a plot, x is the dbh of tree i, and μ is the mean dbh of the plot. Summed values of all trees in a plot are the Gini coefficient and range from 0 to 1 where 0 represent stands that have a perfect size equality where all individuals are equal, and 1 represents stands with a maximum level of size inequality (Weiner and Solbrig 1984; D’Amato et al. 2011).

Compositional complexity

Attributes of stand composition were assessed to quantify the abundance and diversity of tree species within stands. The Shannon's diversity index (Shannon's and Weaver 1949) is a common measure used to assess diversity in forest stands (e.g., Staudhammer and LeMay 2001; D'Amato et al. 2011). Shannon's diversity index was used to quantify species diversity using basal area as the main metric. The Shannon's diversity score for each plot was calculated as:

$$H_{BA} = -\sum_{i=1}^{s} \frac{b_i}{B} \ln\left(\frac{b_i}{B}\right)$$

where s is the number of species in the plot, b_i is the basal area of species $i, and\ B$ is the total basal area on the plot. Species richness of the overstory and woody vegetation in the understory were assessed separately by treatment.

Deadwood

Deadwood was the final component of stand structure assessed for differences based on treatment. Standing dead basal area and trees per hectare were evaluated to assess treatments in standing deadwood structure, calculated as the basal area per hectare on a plot. The other was CWD on the forest floor. Volume of CWD was calculated using the Smalian formula suggested by Woodall & Monleon (2008):

$$CWDVol_{Plot} = \frac{43560}{144}\left[\frac{\sum_t (DS^2 + DL^2)}{L}\right]$$

where $CWDVol_{Plot}$ is the volume of CWD on a plot, DS is the small-end diameter and DL the large-end diameter of piece t, and L is the length of the transect. Large end diameters were predicted using the formula of Woodall et al. (2008):

$$\widehat{DL} = \beta_0 + \beta_1 DT + \beta_2 DC + \beta_3 DTDC$$

where $\widehat{DL}$ is the predicted large-end diameter, DT is the transect diameter, DC is the decay class, and β_i are coefficients specific to softwoods in ecoregion 212.

Statistical analysis

All data analysis was done using R statistical software (R Core Team 2017). One-way analysis of variance (ANOVA) was used to compare the treatment means of stand density, structural complexity, compositional complexity, and deadwood measures. When significant differences ($P < 0.05$) were detected, the 'agricolae' function in R (de Mendiburu 2017) was used to determine which treatments were different by completing post-hoc least significant difference tests using Bonferroni's corrected P-values.

Results

Ten-year post-treatment

Individual plots and compartments had a wide range of conditions prior to treatment in terms of site index, stand ages, and densities (Tables 3.3 and 3.4), but conditions were not statistically different between treatments. After the initial treatment, treatments had a wide range of densities in terms of basal area and trees per hectare (Table 3.5). The shelterwood treatment saw the greatest individual tree diameter increment (Table 3.6), and highest mortality (Table 3.7), resulting in the lowest net basal area growth at the stand level

(Table 3.6). The two selection methods had the next highest individual tree diameter increment, followed by the thinning.

Other than the shelterwood, no other treatments had a negative net basal area growth at the stand level, nor were any other treatments significantly different in terms of stand basal area growth or mortality. Examining the cause of mortality in the shelterwood treatment reveals that 85% of mortality in the shelterwood treatment was caused by wind—either stems breaking or being uprooted (Figure 3-1). Furthermore, residual basal area was lowest in the shelterwood treatment after the initial treatment (Table 3.5).

Long-term post-treatment

Density measures

In 2017, basal area ranged from 17.4 to 39.9 m^2 ha^{-1} across the three treatments (Table 3.8). Mean basal area was significantly higher in the shelterwood treatment (31.3 m^2 ha^{-1}; SD = 3.91) than the patch clear-cut treatment (25.9 m^2 ha^{-1}; SD = 5.72); the strip clear-cut treatment was intermediate with a mean basal area of 29.0 m^2 ha^{-1} (SD = 4.89) that did not differ significantly either of the other treatments. Trees per hectare ranged from 1087.3 to 2841.7. Mean trees per hectare ranged from 1722.5 (SD = 301.7) in the shelterwood treatment to 1988.8 (SD = 406.4) in the clear-cut patch treatment, but was not significantly different between treatments.

Stand structure

In 2017, the three treatments saw significant differences in all three individual tree attributes representing stand structure complexity (Table 3.9). Individual tree dbhs ranged

Table 3.3. Mean, standard deviation, and range of site index and age in six silvicultural treatments and the control in 1948 on the Big Falls Experimental Forest in northern Minnesota, USA

Treatment	n plots	Site index (m at 100 yrs)			Age (yrs)		
		Mean	SD	Range	Mean	SD	Range
Thinning	26	12.8	2.1	9.1-15.2	140.0	37.9	90-180
Shelterwood	30	16.2	1.5	15.2-18.3	113.3	36.5	70-160
CC strips	48	13.6	2.4	9.1-18.3	134.6	14.3	100-150
CC patches	43	12.8	1.5	9.1-15.2	119.1	44.0	70-180
Group sel.	37	15.0	1.3	12.2-18.3	98.4	33.9	70-180
Tree sel.	30	13.4	2.0	9.1-15.2	117.3	27.3	70-150
Control	23	13.1	2.8	9.1-18.3	106.1	27.3	70-130

Table 3.4. Mean, standard deviation, and range of pre-treatment density measures (basal area ha and trees ha) in six silvicultural treatments and the control in 1948 on the Big Falls Experimental Forest in northern Minnesota, USA

Treatment	n plots	Basal area (m^2 ha^{-1})			Trees (Trees ha^{-1})		
		Mean	SD	Range	Mean	SD	Range
Thinning	26	30.3	4.4	21.5-36.6	2125	456.4	1334-3163
Shelterwood	30	30.0	4.7	17.6-38.0	1613	426.5	618-2446
CC strips	48	28.6	6.0	12.5-39.0	1725	524.6	717-2866
CC patches	43	27.4	5.9	16.3-37.5	1927	423.0	988-2496
Group sel.	37	30.5	5.6	16.0-38.6	1921	428.0	840-2669
Tree sel.	30	27.2	6.4	15.4-39.9	1753	526.8	642-2916
Control	23	25.8	6.5	10.7-33.7	1780	381.3	1013-2570

Table 3.5. Mean, standard deviation, and range of stand conditions after initial treatment in each silvicultural treatment in 1950 of plots used in a ten-year diameter growth model on the Big Falls Experimental Forest in northern Minnesota, USA

Treatment	n		Basal area (ft^2 ha^{-1})			Trees (Trees ha^{-1})		
	Plots	Trees	Mean	SD	Range	Mean	SD	Range
Thinning	26	1,425	21.9	2.9	16.3-26.5	1443	277.3	964-2026
Shelterwood	30	423	11.8	2.5	6.9-17.4	493	105.0	297-717
CC strips	37	2,396	28.0	6.2	12.5-39.0	1718	566.6	717-2866
CC patches	27	1,997	28.1	5.3	17.9-37.5	1920	435.9	988-2496
Group sel.	25	1,161	20.1	3.4	13.0-27.2	1247	286.6	667-1705
Tree sel.	30	1,254	17.5	5.1	9.8-32.4	1111	336.8	395-1680
Control	23	1,580	25.8	6.5	11.4-33.7	1780	381.3	1013-2570

Table 3.6. Mean, standard error, and range of dbh increment and net basal area increment in residual plots in peatland black spruce ten years after initial silvicultural treatment on the Big Falls Experimental Forest, northern Minnesota, USA. Letters denote significant differences.

Treatment	n		Tree dbh increment (cm)			Net stand basal area increment (m^2 ha^{-1})		
	Plots	Trees	Mean	SD	Range	Mean	SD	Range
Shelterwood	30	423	2.4[a]	0.98	0.3-5.6	-1.9[a]	5.2	-14.3-4.6
CC strips	37	2,396	1.4[d]	0.65	0-4.8	3.1[b]	3.2	-9.5-7.2
CC patches	27	1,997	1.3[e]	0.63	0-3.6	4.1[b]	1.6	-0.5-6.6
Group Sel.	25	1,161	1.8[b]	0.71	0-4.6	3.4[b]	1.5	-0.3-6.1
Tree Sel.	30	1,254	1.8[b]	0.79	0-6.3	2.8[b]	2.4	-3.3-6.1
Thinning	26	1,425	1.5[c]	0.63	0-4.1	3.4[b]	3.8	-13.9-6.3
Control	23	1,580	1.4[d]	0.69	0-4.5	4.0[b]	1.7	1.5-7.0

Table 3.7. Percent mortality mean, SD, and range of individual tree mortality in peatland black spruce by treatment ten years after initial silvicultural treatment on the Big Falls Experimental Forest, northern Minnesota, USA. Letters denote significant differences.

Treatment	**n trees**		**% Mortality**		
	Total	**Died**	**Mean**	**SD**	**Range**
Shelterwood	598	159	29.3%[a]	26.2%	0-78.9%
CC strips	2,985	162	7.1%[b]	7.6%	0-38.7%
CC patches	3,203	97	4.5%[b]	5.0%	0-20.3%
Group Sel.	1,263	56	4.7%[b]	3.5%	0-12.3%
Tree Sel.	1,352	74	6.7%[b]	9.6%	0-43.8%
Thinning	1,518	95	7.2%[b]	11.8%	0-61.5%
Control	1,657	66	3.8%[b]	3.0%	0-9.8%

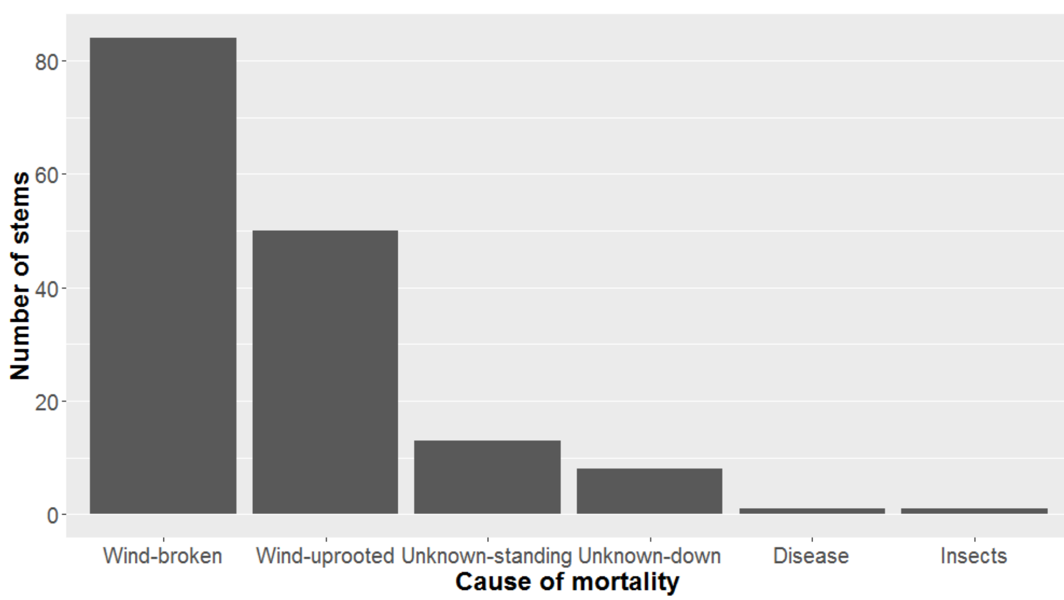

Figure 3-1. The number of stems that died by each cause in the shelterwood treatment in lowland black spruce 10 years after harvest in the Big Falls Experimental Forest, northern Minnesota, USA

from 8.4 to 35.3 cm. Mean dbh was 12.8 cm (SD = 2.02) in the patch clear-cut and 13.7 cm (SD = 1.49) in the strip clear-cut. The shelterwood saw a significantly higher average dbh at 14.8 cm (SD = 1.08). Heights ranged from 9.2 to 22.9 m, with mean height significantly greater in the shelterwood treatment than the clear-cut treatments at 17.5 m (SD = 1.45). UCR was highest in the strip clear-cut treatment at 0.541 (SD = 0.142), significantly higher than the shelterwood treatment at 0.473 (SD = 0.112) but not significantly different than the clear-cut patch treatment.

Plotting stand composition by the total number of trees by species in 5 cm size classes shows substantial differences in size and species composition in the three treatments (Figure 3-2). The clear-cut treatments have a greater number of smaller diameter trees than the shelterwood treatment. Additionally, the shelterwood has a greater proportion of the stand consisting of species other than black spruce, including tamarack (*Larix laricina* (Du Roi) K. Koch), paper birch (*Betula papyrifera* Marshall), and balsam fir (*Abies balsamea* (L.) Miller).

The Gini coefficient representing tree size inequality showed that all three treatments had significantly different values (Table 3.12). Values ranged from 0.064 to 0.179, and the lowest treatment mean—representing less size inequality—occurred in the patch clear-cut treatment at 0.106 (SD = 0.023). The shelterwood treatment had the highest value—equating to greater size inequality—at 0.150 (SD = 0.016).

Measures of deadwood structure—both standing and downed—did not find differences between treatments (Table 3.10). Mean basal area of standing deadwood was around 2% of live basal area in all treatments, with mean basal area per plot ranging from 0.57 to 0.85 m^2 ha^{-1}. There were not significant differences between treatments. Mean dead trees per hectare ranged from 40.4 trees to 65.9 trees and was also not significantly different between treatments. Volume of CWD was significantly greater in the shelterwood treatment than the clear-cut treatments with a mean volume of 16.5 m^3 ha^{-1} (SD = 14.5) compared to 5.8 m^3 ha^{-1} (SD = 10.1) and 4.7 m^3 ha^{-1} (SD = 12.2) in the clear-cut patches and clear-cut strips respectively.

Stand composition

The stand composition measures varied by treatment. Species richness of understory woody species, including regeneration, was significantly higher in the shelterwood treatment at 2.94 species (SD = 1.48) than either the clear-cut strips (mean = 1.81, SD = 0.780 species) or the clear-cut patches (mean = 1.90, SD = 0.724 species) treatments (Figure 3-2). In the overstory, there were significantly more species the shelterwood (mean = 3.35, SD = 0.702 species) and the clear-cut strips (mean = 2.91, SD = 0.995 species) treatments than in the clear-cut patches treatments (mean = 2.241, SD = 0.577 species). Mean Shannon's diversity of the overstory was greatest in the shelterwood treatment at 0.891 (SD = 0.187) and least in the patch clear-cut treatment (0.413; SD = 0.185 [Figure 3-3]).

Discussion

The shelterwood treatment saw, by far, the greatest increase in individual diameter growth in residual stems when compared with the other treatments. However, the gains in individual tree diameter growth in the shelterwood treatment were offset by being the only treatment with significantly higher mortality when compared with other treatments, and the only treatment with net negative basal area growth. The main goal of a shelterwood system is typically not to increase the growth rate of residual trees

Table 3.8. Mean, standard error, and range of basal area and trees per hectare of three silvicultural treatments 50 to 57 years after final regeneration harvest on the Big Falls Experimental Forest, northern Minnesota, USA. Letters denote significant differences.

		Live basal area ($m^2\ ha^{-1}$)			Live trees (Trees ha^{-1})		
Treatment	n	mean	SD	Range	mean	SD	Range
Shelterwood	17	31.3[a]	3.91	22.8 – 36.9	1722.5[a]	301.7	1334.4 – 2248.7
CC strips	32	29.0[ab]	4.89	19.4 – 39.0	1901.2[a]	454.6	1087.3 – 2668.7
CC patches	29	25.9[b]	5.72	17.4 – 39.9	1988.8[a]	406.4	1210.8 – 2841.7

Table 3.9. Mean, standard error, and range of diameter at breast height, total height, and uncompacted live crown ratio of three silvicultural treatments 50 to 57 years after final regeneration harvest in lowland black spruce on the Big Falls Experimental Forest, northern Minnesota, USA. Letters denote significant differences.

	dbh (cm)				ht (m)				UCR (ratio)			
Treatment	n	mean	SD	Range	n	mean	SD	Range	n	mean	SD	Range
Shelterwood	1185	14.8[a]	1.08	8.9 – 26.7	49	17.5[a]	1.45	14.5 – 20.9	49	0.47[b]	0.112	0.25-0.72
Strip CC	2461	13.7[ab]	1.49	8.4 – 35.3	91	14.1[b]	1.97	9.2 – 20.7	92	0.54[a]	0.142	0.19-0.90
Patch CC	2334	12.8[b]	2.02	9.1 – 31.5	88	13.7[b]	2.09	10.1 – 22.9	85	0.50[ab]	0.138	0.27-0.82

Table 3.10. Mean, standard deviation, and range of standing dead basal area and standing dead trees per hectare, and volume of coarse woody debris on the forest floor in three silvicultural treatments 50 to 57 years after final regeneration harvest on the Big Falls Experimental Forest, northern Minnesota, USA. Letters denote significant differences.

		Dead BA ($m^2\ ha^{-1}$)			Dead TPH (Trees ha^{-1})			CWD Volume ($m^3\ ha^{-1}$)		
Treatment	n	mean	SD	Range	mean	SD	Range	mean	SD	Range
Shelterwood	17	0.85[a]	0.67	0.2 – 2.0	65.9[a]	48.2	24.7 – 173.0	16.5[a]	14.5	0 – 42.4
Strip CC	32	0.72[a]	0.53	0.2 – 2.2	54.9[a]	31.2	24.7 – 98.8	4.7[b]	10.2	0 – 40.3
Patch CC	27	0.57[a]	0.67	0.2 – 2.2	40.4[a]	35.4	24.7 – 123.6	5.8[b]	12.2	0 – 55.0

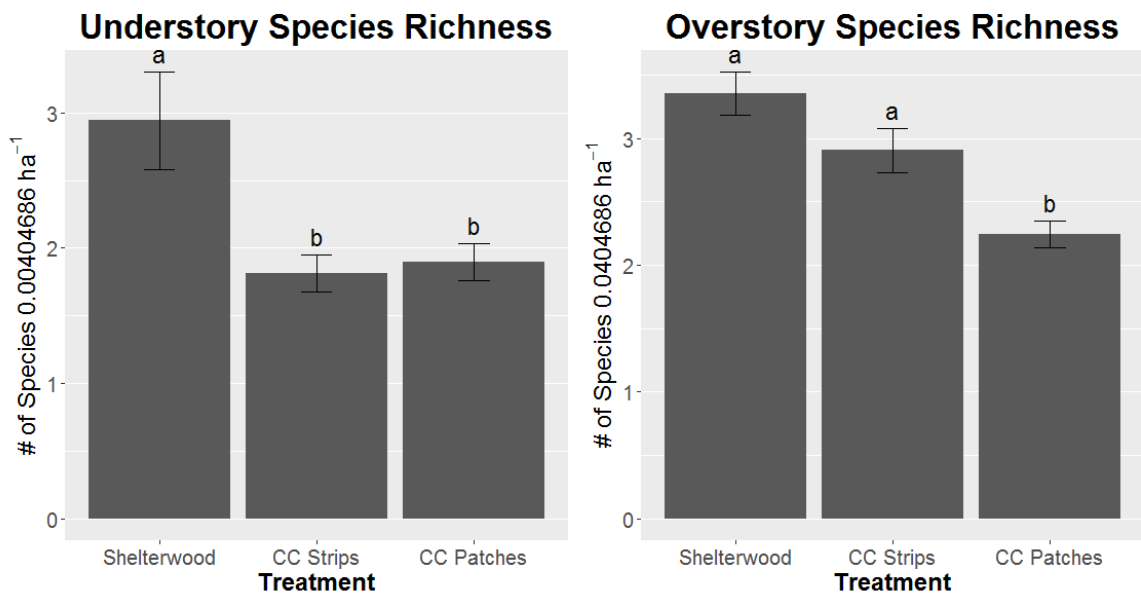

Figure 3-2. Species richness of the understory and overstory in three silvicultural treatments 50 to 57 years after final regeneration harvest on the Big Falls Experimental Forest, northern Minnesota, USA. Letters denote significant differences.

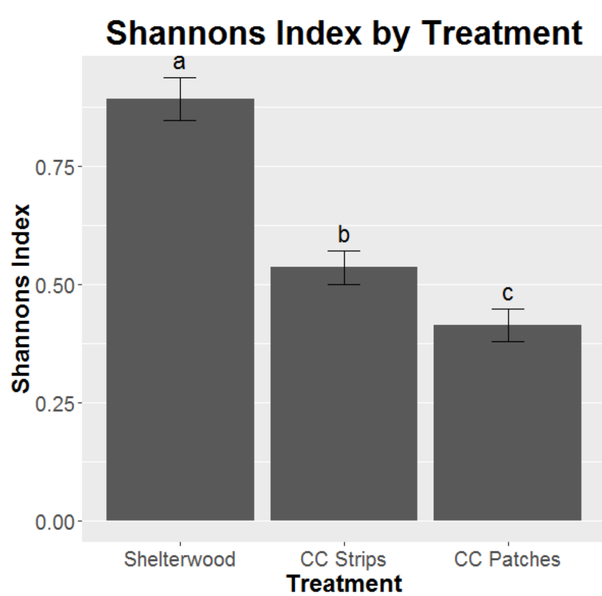

Figure 3-3. Shannon's diversity index of the overstory in three silvicultural treatments 50 to 57 years after final regeneration harvest on the Big Falls Experimental Forest, northern Minnesota, USA. Letters denote significant differences.

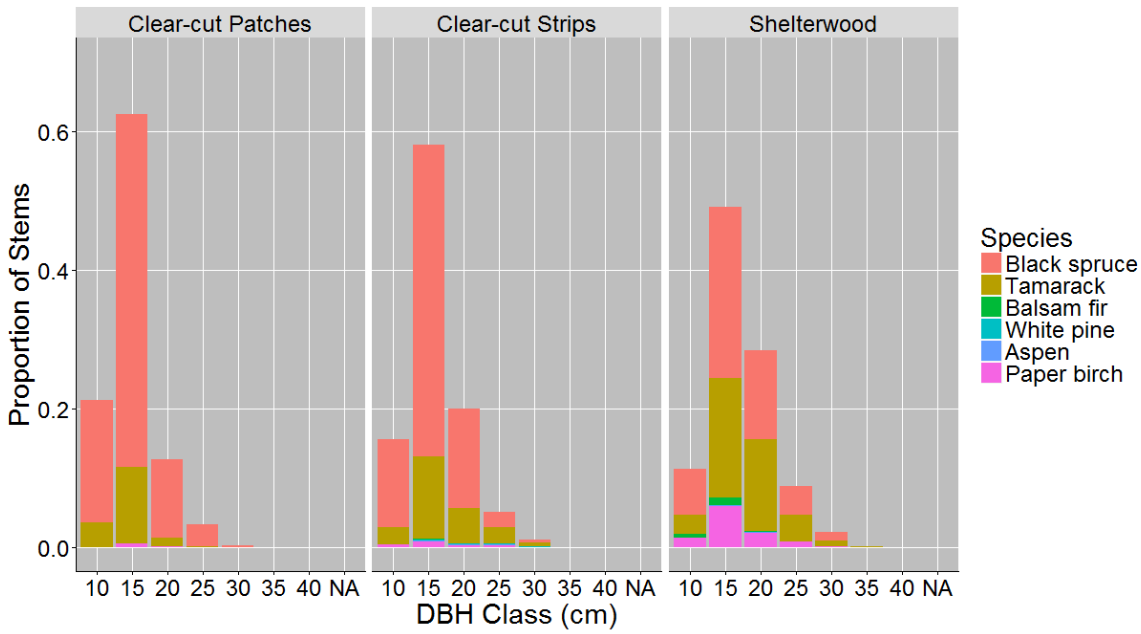

Figure 3-4. Species mix by diameter distribution in lowland black spruce 50 to 57 years after final regeneration harvest in three silvicultural treatments on the Big Falls Experimental Forest, northern Minnesota, USA.

Table 3.11. Mean, standard deviation, and range of the Gini Coefficient depicting tree size inequality in three silvicultural treatments 50 to 57 years after final regeneration harvest on the Big Falls Experimental Forest, northern Minnesota, USA. Letters denote s

		Gini Coefficient		
Treatment	n	mean	SD	Range
Shelterwood	17	0.150[a]	0.016	0.119 – 0.177
Strip CC	32	0.131[b]	0.029	0.067 – 0.179
Patch CC	29	0.106[c]	0.023	0.064 – 0.151

(Girona et al. 2016), but to serve as a seed source and protection for advance regeneration that is present (Nyland 2007). Measurements collected in 2017 show that those goals were accomplished in the shelterwood treatment, despite the original high mortality of residual trees. To decrease mortality of residual trees prior to overstory removal, a higher residual stocking can decrease wind exposure while still providing a seed source and protection for advance regeneration (Nyland 2007). This may be particularly important in the Lake States where high severity wind events can occur frequently, and in black spruce stands which are highly susceptible to wind-breakage and tip-up due to their shallow-rootedness (Viereck and Johnston 1990). An aggregated shelterwood preserving residual trees around pockets of significant or larger advance regeneration may also reduce wind mortality while accomplishing the regeneration and production goals of a shelterwood and potentially making the overstory removal more profitable and logistically feasible.

The shelterwood treatment resulted in tradeoffs in stand density and structure in the short- and long-term. After ten years, the shelterwood treatment resulted in increased diameter growth of residual trees but higher mortality and net negative basal area change in residual stems over 12.7 cm. Over the long-term, the shelterwood treatment resulted in stand conditions that many forest managers may consider more ideal than either of the clear-cut systems. Individual trees in the shelterwood treatment had larger diameters and heights, while stands contained fewer trees with higher basal area per hectares. Stand structure as defined by the Gini coefficient had greater inequality in the shelterwood treatment, and diversity was greater as measured by the Shannon's diversity index of overstory trees and the species richness of woody understory species, including regeneration. This may provide additional resilience in the face of disturbance, increased wildlife habitat, and a greater variety of economic products. Larger trees in the shelterwood treatment than the clear-cut treatments over the same period suggest that rotation ages could be shortened by using a shelterwood system. Additionally, the more complex structure of a shelterwood system may benefit wildlife species such as snowshoe hare, spruce grouse, and American marten (Cimon-Morin et al. 2010).

Mistletoe was recorded as being present in only two of the 36,692 trees measured in the original measurements and was not found in the 2017 re-measurement. As such, mistletoe was not a major component in any of the treatments and this study is generally unaffected by mistletoe. Mistletoe is a persistent problem in lowland black spruce stands in Minnesota (Baker et al. 2012). Recommended management in affected stands is to cut all trees greater than 1.5 m (five ft) in height, and create a buffer of 20 to 40 m around any infection. Shelterwood and selection methods—both individual tree and group selection—would not meet the management recommendations and would not rid infected stands of mistletoe. Additionally, dwarf mistletoe spreads more quickly in less dense stands (Johnston 1977a). The shelterwood system resulted in slightly (albeit not significantly) less dense stands than the clear-cut systems after 50 to 57 years. Patch clear-cuts or strip clear-cuts may be successfully implemented if a wide enough buffer is cut to remove possible latent infections. Commercial thinning may be compatible with mistletoe infected stands if individuals with mistletoe are selected for removal, and if a regeneration harvest takes place soon after thinning so that the spread of mistletoe is halted. This may allow managers to have a commercially viable thinning, select risk trees to remove, including trees with mistletoe, and increase the growth of residuals, decrease time to the regeneration harvest and increase stand productivity.

The wide array of age classes at the time the study was initiated is reflective of the range of age classes in Minnesota and the Lake States, broadly. Stands that have not been extensively managed have also escaped stand-replacing fires and are, as a result, older in age. Stand structure has become uneven-aged with multiple cohorts. There has been particular interest in Canada in the use of alternative silvicultural systems (i.e., shelterwood, CLAAG, HARP) to the oft-used clear-cutting methods where uneven-aged stand conditions have developed (Groot 2002; Groot et al. 2005; Pamerleau-Couture et al. 2015). Lowland black spruce in Minnesota, while not having the same extensive recent research, likely can be managed with the same systems. However, as Groot et al. (2005) point out, the first implementation of a shelterwood system will likely be the last. After a shelterwood system is implemented, stands are more likely even-aged, even after a shelterwood that takes advantage of advance regeneration (Groot and Horton 1994).

Conclusion

This study helps to fill key gaps in the understanding of stand dynamics in lowland black spruce *(Picea mariana* (Miller) B.S.P.) over nearly 70 years in the Lake States, USA. A shelterwood system may fulfill a number of objectives of a forest manager over time by providing protection and a seed source while increasing residual tree growth in the short-term, and increasing structural and compositional complexity and diversity while increasing stand basal area over the long-term. Care must be taken to ensure that proper silvicultural systems are used when disturbance agents such as dwarf mistletoe or severe wind events may threaten black spruce forests. Patch and strip clear-cuts may be more viable in cases where either damaging agents are present. Clear-cut strips and patches and shelterwood systems could serve as additional tools for use in a manger's tool belt in lowland black spruce.

Chapter 4 Conclusion and management implications

Long-term silvicultural studies are extremely valuable, particularly in slow-growing cover types such as black spruce. Studies following stand development of lowland black spruce stands over extended periods of time in the Lake States do not exist, particularly those following a stand over the majority of its lifecycle or rotation age. Quantifying how various silvicultural systems affect lowland black spruce stands is important to provide managers with a likely view of future conditions.

The Compartment Study on the Big Falls Experimental Forest provided a key opportunity to understand how non-traditional silvicultural systems and management in black spruce affected stands in both the short-term (ten years) and long-term (50 to 57 years), the latter of which is approaching a typical rotation age of black spruce forests.

The mixed-effects diameter growth model was adapted relatively easily to lowland black spruce in Minnesota and performed very well in predicting ten-year diameter growth. The model may provide improvements over those currently in use in common growth and yield models (e.g., FVS), though the Deo & Froese (2013) model has been proven successful and is in the process of being incorporated into FVS.

The results of this study support the use of shelterwood systems in lowland black spruce in northern Minnesota, particularly where stands have advanced in age and have developed into uneven-aged stands where advance regeneration is already present. Short-term increases in growth were offset by high rates of mortality in the shelterwood system, but long-term stand conditions resulted in more structurally and compositionally diverse stands which is beneficial for wildlife habitat (Cimon-Morin et al. 2010), mitigating risks from damaging agents such as pathogens and diseases (Haas et al. 2011), and provides managers more options for stands moving forward. Furthermore, trees in the shelterwood treatment were less dense (fewer trees per hectare), taller, and had larger diameters than those in either clear-cut method.

When eastern spruce dwarf mistletoe is present, managers must take proactive action to rid a stand of the parasitic plant. Traditional clear-cutting or clear-cut patches and strips of a large enough size are an option for eliminating mistletoe from future stands if it is present.

Due to the facts that this study did not test a traditional clear-cutting method, the control treatment was lost due to unrelated harvesting, and that there is a lack of long-term studies in lowland black spruce in the Lake States, comparisons of the tested metrics in this study to unmanaged stands or stands utilizing traditional clearcutting was not easy. However, the results of this study do provide insight into three alternative silvicultural systems and gives managers a means to compare future conditions. It is the hope that these results may provide additional tools for managers of Minnesota's extensive black spruce forests in the wake of shifting attitudes towards traditional clear-cutting, the presence of mistletoe, and the aging black spruce populations in Minnesota.

References

Aaeseng N, Almendinger J, Rusterholz K, et al (2003) Field guide to the native plant communities of Minnesota: The Laurentian Mixed Forest Province. Minnesota Department of Natural Resources, Saint Paul, MN

Baker FA, O'Brien JG, Mathiasen R, Ostry ME (2006) Eastern spruce dwarf mistletoe.

Baker F, Hansen M, Shaw JD, et al (2012) The incidence of dwarf mistletoe in Minnesota black spruce stands detected by operational inventories. North J Appl For 29:109–112.

Cimon-Morin J, Ruel JC, Darveau M (2010) Short term effects of alternative silvicultural treatments on stand attributes in irregular balsam fir-black spruce stands. For Ecol Manage 260:907–914. doi: 10.1016/j.foreco.2010.06.010

D'Amato AW, Bradford JB, Fraver S, Palik BJ (2011) Forest management for mitigation and adaptation to climate change: Insights from long-term silviculture experiments. For Ecol Manage 262:803–816. doi: 10.1016/j.foreco.2011.05.014

de Mendiburu F (2017) agricolae: statistical procedures for agricultural research. R Package version 1.2-8. https://cran.r-project.org/package=agricolae.

Deans AM, Malcolm JR, Smith SM, Carleton TJ (2003) A comparison of forest structure among old-growth, variable retention harvested, and clearcut peatland black spruce (Picea mariana) forests in boreal northeastern Ontario. For Chron 79:579–589. doi: 10.5558/tfc79579-3

Deo RK, Froese RE (2013) Refitting the Large-Tree Diameter Growth Equations of the Lake States and Central States Variants of the Forest Vegetation Simulator.

Dixon GE, Keyser CE (2017) Lake States (LS) Variant Overview; Forest Vegetation Simulator. Fort Collins, CO

Fox GD, Kruse GW (1933) A yield table for well-stocked stands of black spruce in northeastern Minnesota. J For 37:565–567.

Girona MM, Morin H, Lussier JM, Walsh D (2016) Radial growth response of black spruce stands ten years after experimental shelterwoods and seed-tree cuttings in boreal forest. Forests 7:1–20. doi: 10.3390/f7100240

Groot A (1995) Silvicultural systems for black spruce ecosystems. In: Innovative silviculture systems in boreal forests. Edmonton, Alberta, pp 47–51

Groot A (2014) Fifteen-year results of black spruce uneven-aged silviculture in Ontario, Canada. Forestry 87:99–107. doi: 10.1093/forestry/cpt021

Groot A (2002) Is uneven-aged silviculture applicable to peatland black spruce (Picea mariana) in Ontario, Canada? Forestry 75:437–442. doi: 10.1093/forestry/75.4.437

Groot A, Hökkä H (2000) Persistence of suppression effects on peatland black spruce advance regeneration after overstory removal. Can J For Res 30:753–760.

Groot A, Horton BJ (1994) Age and size structure of natural and second-growth peatland Picea Mariana stands. Can J For Res 24:225–233.

Groot A, Lussier JM, Mitchell AK, Maclsaac DA (2005) A silvicultural systems perspective on changing Canadian forestry practices. For Chron 81:50–55. doi: 10.5558/tfc81050-1

Haas SE, Hooten MB, Rizzo DM, Meentemeyer RK (2011) Forest species diversity reduces disease risk in a generalist plant pathogen invasion. Ecol Lett 14:1108–1116. doi: 10.1111/j.1461-0248.2011.01679.x

Hann DW, Marshall DD, Hanus ML (2003) Equations for predicting height-to-crown

base, 5-year diameter growth rate, 5-year height-growth rate, 5-year mortality rate, and maximum size-density trajectory for douglas-fir and western hemlock in the coastal region of the pacific northwest. Corvallis, OR
Heinselman ML (1957) Silvical characteristics of black spruce (Picea mariana). St. Paul, MN
Heinselman ML (1959) Natural regeneration of swamp black spruce in Minnesota under various cutting systems. Washington, D.C.
Johnston WF (1977a) Manager’s handbook for black spruce in the north central States.
Johnston WF (1977b) Final report summary: compartment study of cutting methods in swamp black spruce. Grand Rapids, MN
Johnston WF, Smith TM (1983) Black spruce. In: Burns RM (ed) Silvicultural systems for the major forest types of the United States. U.S. Department of Agriculture, Agriculture Handbook, Washington, D.C., pp 96–98
Kolabinski VS (1991) Effects of cutting method and seedbed treatment on black spruce regeneration in Manitoba.
Lafleur B, Renard S, Leroy C, et al (2016) Silviculture to sustain productivity in black spruce paludified forests. For Ecol Manage 375:172–181. doi: 10.1016/j.foreco.2016.05.037
LeBarron RK (1945) Light cutting in black spruce is practicable. J For 43:486–489.
Lumley T based on R code by AM (2017) leaps: Regression Subset Selection. R package version 3.0. https://cran.r-project.org/package=leaps.
MacDonell MR, Groot A (1997) Uneven-aged silviculture for peatland second-growth black spruce: biological feasibility. Surrey, British Columbia, Canada
Miles PD (2017) Forest Inventory EVALIDator web-application Version 1.6.0.03. http://apps.fs.fed.us/Evalidator/evalidator.jsp. Accessed 17 Apr 2017
Minnesota Department of Conservation; USDA Forest Service (1948) Memorandum of understanding between the Minnesota Department of Conservation and the Forest Service, United States Department of Agriculture covering conduct of forest management experiments.
Minnesota Department of Natural Resources (2017) Minnesota’s Forest Resources 2016. Saint Paul, MN
Nyland RD (2007) Silviculture concepts and applications, 2nd edn. Waveland Press, Inc., Long Grove, IL, USA
Pamerleau-Couture É, Krause C, Pothier D, Weiskittel A (2015) Effect of three partial cutting practices on stand structure and growth of residual black spruce trees in north-eastern Quebec. Forestry 88:471–483. doi: 10.1093/forestry/cpv017
Perala DA (1971) Growth and yield of black spruce on organic soils in Minnesota. Research Paper NC-56. St. Paul, MN: USDA Forest Service, North Central Forest Experiment Station
Pinheiro J, Bates D, DebRoy S, et al (2017) Linear and nonlinear mixed effects models. https://cran.r-project.org/package=nlme.
R Core Team (2017) R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.r-project.org/.
Schantz-Hansen T (1931) Preliminary Observations on the Use of Clear Cut Strips in Handling Black Spruce. J For 29:1168–1172.
Shannon CE, Weaver W (1949) The mathematical theory of communication. University

of Illinois Press, Urbana, IL
Smith-Mateja E (2018) Personal communication.
Soucy M, Lussier J-M, Lavoie L (2012) Long-term effects of thinning on growth and yield of an upland black spruce stand. Can J For Res 42:1669–1677. doi: 10.1139/x2012-107
Staudhammer CL, LeMay VM (2001) Introduction and evaluation of possible indices of stand structural diversity. Can J For Res 31:1105–1115. doi: 10.1139/x01-033
Subedi N, Sharma M (2011) Forest Ecology and Management Individual-tree diameter growth models for black spruce and jack pine plantations in northern Ontario. For Ecol Manage 261:2140–2148. doi: 10.1016/j.foreco.2011.03.010
Thorpe HC, Thomas SC (2007) Partial harvesting in the Canadian boreal: Success will depend on stand dynamic responses. For Chron 83:319–325. doi: 10.5558/tfc83319-3
USDA Forest Service (2013) Lake States (LS) Variant Overview, Forest Vegetation Simulator. Fort Collins, CO
USDA Forest Service (1948) Working plan for compartment study of cutting methods in swamp black spruce - Big Falls Experimental Forest. Grand Rapids, MN
USDA Forest Service (2011) Forest Inventory and Analysis Phase 3 Guide – Downed Woody Materials, Version 5.1.
Viereck LA, Johnston WF (1990) Picea mariana (Mill.) B. S. P. In: Burns RM, Honkala BH (eds) In Silvics of North America: Volume 1 - conifers. Agriculture Handbook 654. USDA Forest Service. Washington, D.C., p 877
Vincent M, Krause C, Zhang SY (2009) Radial growth response of black spruce roots and stems to commercial thinning in the boreal forest. Forestry 82:557–571. doi: 10.1093/forestry/cpp025
Weetman GF (1975) Ten-year growth response of black spruce to thinning and fertilization treatments. Can J For Res 5:302–309.
Weiner J, Solbrig OT (1984) The meaning and measurement of size hierarchies in plant populations. Oceologia 61:334–336.
Weiskittel AR, Garber SM, Johnson GP, et al (2007) Annualized diameter and height growth equations for Pacific Northwest plantation-grown Douglas-fir, western hemlock, and red alder. For Ecol Manage 250:266–278. doi: 10.1016/j.foreco.2007.05.026
Woodall CW, Monleon VJ (2008) Sampling protocol, estimation, and analysis procedures for the down woody materials indicator of the FIA Program.
Woodall CW, Westfall JA, Lutes DC, Oswalt SN (2008) End-point diameter and total length coarse woody debris models for the United States. For Ecol Manage 255:3700–3706. doi: 10.1016/j.foreco.2008.03.027
Youngblood A, Titus B (1996) Clearcutting-a regeneration method in the boreal forest. For Chron 72:31–36.